MEASUREMENT OF THE AGE TO INDIUM RESONANCE OF PLUTONIUM - BERYLLIUM SOURCE NEUTRONS IN AIR WATER MIXTURES

BY

SHRAVAN KUMAR GUPTA

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

SEPTEMBER 1972

MEASUREMENT OF THE AGE TO INDIUM RESONANCE OF PLUTONIUM - BERYLLIUM SOURCE NEUTRONS IN AIR WATER MIXTURES

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

BY
SHRAVAN KUMAR GUPTA

to the

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

SEPTEMBER 1972

C E R T I F I C A T E

This is to certify that the present work "Measurement of the Age to Indium Resonance of Plutonium - Beryllium Source Neutrons in Air Water Mixtures" by S.K. Gupta has been carried out under my supervision and the work has not been submitted elsewhere for a degree.

G. SRIKANTIAH
Professor and Head
Department of Mechanical Engineering
Indian Institute of Technology
Kanpur

ACKNOWLEDGEMENT

The completion of an experimental work of this kind depends upon the assistance and cooperation of many persons. The research scholar is grateful to Mr. V.P. Chacko of Chemistry Department, IIT Madras, Mr. M.G. Subramanian of Mechanical Engineering Department, IIT Kanpur and Mr. P.N. Mishra of Mechanical Engineering Department, IIT Kanpur for the help rendered in setting up the experiment.

Thanks are also due to Dr. P.S. Goel of Chemistry Department, Dr. D. Ramakrishna of Chemical Engineering and Dr. D. Devaprabhakara of Chemistry Department for the facility extended by them in the course of the experiment.

He is also grateful for the valuable suggestions and criticism he received from Dr. K. Sri Ram of Mechanical Engineering Department, IIT Kanpur.

The writer is deeply appreciative of the guidance he received from Dr. G. Srikantiah, Professor and Head of the Mechanical Engineering Department, IIT Kanpur.

S K G

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

τ	= Neutron age
r	= Radial distance from neutron source
$q(r,E)$	= Neutron slowing down density past the energy E at a distance r
S	= Strength of source
$S(E)$	= Energy spectrum of neutron source
$q(r,E \to E_f)$	= Slowing down kernel
$A_s(r)$	= Saturation activity of the foil at a distance r from the source
V	= Volume of an activation foil
$\phi(r,E)$	= Energy dependent neutron flux at a distance r from the source
$\Sigma_a(E)$	= Energy dependent macroscopic absorption cross section of the foil
$\Sigma_{sm}(E)$	= Energy dependent macroscopic scatt. cross section of the medium in which the foil is immersed
ξ	= Average logarithimic energy decrement in the medium in which the foil is immersed
t	= Time
B	= Background counts
C	= Counts observed with a foil
η	= Counting efficiency of the counter
t_c	= Counting time for each side of a foil

ABSTRACT

The aim of the present experiment is to study the slowing down of neutrons from a Pu - Be neutron source in a mixture of air and water in which the air bubbles through the water at a very slow rate. The volume fraction defined as the volume of air to volume of water was of the order of 40×10^{-5}. The age of Pu - Be neutrons to Indium resonance has been measured at three different air flow rates viz. 18,000 cc/min., 36,000 cc/min. and 54,000 cc/min. The air was supplied at a pressure of $20 \pm .5$ psi.

In order to do this nearly 1500 litres of light water was stored in an aluminium tank. In this tank six equally spaced aluminium tubes of half inch inner diameter were held with their axes horizontal. Each tube was drilled with twenty one equally spaced holes of diameter .0605''. Equal amount of purified air was supplied to each tube. This air had to come out from .0605'' diameter holes in the form of bubbles and travel through the water to the top of the tank.

The flux perturbation due to the introduction of different materials in the moderator is minimised by us..g a minimum of structural material to hold the

source and to suspend the foils. Approximate corrections are applied to the measured activities to correct them for the high energy activation and the finite size of the source and the foil. Finally the statistical errors in the measured values, due to the statistical errors in the measured activities are calculated.

The neutron age for the air flow rates at 18000 cc/min., 36000 cc/min., 54000 cc/min. are found to be 67.18 ± 3.28, 70.76 ± 2.57, 75.28 ± 2.87 respectively.

This indicates that there is an increase of 33% compared to the age in pure water.

CHAPTER I

INTRODUCTION

1.1. Purpose of the Experiment

The age of neutrons in a moderating medium is defined as one sixth of the average square distance a neutron travels during slowing down from a high energy to a low energy. The age is dependent on the microscopic properties of the moderating medium and its determination is a macroscopic measurement.

In Boiling Water Reactor, water acts as a moderator as well as an agent to remove the heat from the system. This water as it passes through the system gets partly vapourised to form a hetrogeneous mixture of steam bubbles and water. In the present work similar conditions have been simulated by passing air through the light water. The purpose is to study this macroscopic parameter, age when the nucleation just starts in a corresponding boiling water system. The age of neutron has been measured for three different flow rates starting from the point when the air just starts coming out.

In the past few years, age measurements in different media with different sources have been

carried out. Literature survey reveals that no one has measured the age in a mixture of air and water. Also there is no theoretical calculation of age in such a system.

1.2. Age in Water

Both experimental and theoretical determination of neutron age from fission and other sources to Indium resonance in pure water are available. Table 1 is a list of almost all neutron age determinations in water. In general the experimental values are higher than the theoretical values. This disagreement has been well understood in case of the age of fission neutrons in water. Hary Atler (8) has made monte carlo calculations for the age of fission neutrons in water including inelastic scattering and amisotropic elastic scattering effects, using different fission spectra and different sets of oxygen cross-section and angular distribution data. The calculated value of the slowing down age after applying suitable corrections compares well with the experimental flux ages.

J.W. Cooper has made monte carlo calculations for the age of D.D. neutrons in water using different duct sizes for the deutron beam and two different deutron energies. The computed values compares well with the experimental values.

TABLE 1. NEUTRON AGE TO INDIUM RESONANCE

Year	Investigator and Method	Medium	Source	Age in cm^2
1961	Dorner et al[1*] FA	Water	Fission	27.86 ± 0.10
1961	J.W. Cooper[2] MC	Water	D - D	Table in Reference
1961	Amster and Gast[3] FA	Water	Fission	25.2 ± 0.11
			Na - Be	$13.33 + 0.05$
1961	De Juren et al[4] FA	Water	1.4 MEV D - D	54.4 ± 1.4
1961	Amster and Gast[5] FA and MC	Water	D - D	63.0 ± 0.5 64.5 ± 0.5
1962	Joanou et al[6] MM	Water	Fission	26.4
			Po - Be	58.5 ± 1.5
			Na^{24} - Be	14.0
			N^{17}	14.5
			Ra - Be	56.7
1964	R.K. Paschall[7] FA	Water	Fission	$26.8 \pm .32$
1965	Harry Alter[8] MC	Water	Fission	Tables in References

FA = Foil activation method

MC = Monte carlo calculation

MM = Moments method

* Number in the superscript refer to similarly numbered references at the end of the thesis.

CHAPTER II

AGE MEASUREMENT TECHNIQUE

2.1 Definition of Neutron Age

The neutron age from an energy E_0 (well above the thermal region) to a lower energy E in a non-absorbing moderating medium is defined as 1/6th of the average of the square of the crow flight distance that a neutron emitted by a point isotropic steady monoenergetic source of energy E_0 travels in an infinite bulk of the moderating medium to the point where it slows down past the energy E.

Let r = The radial (or crow flight) distance from the source to a point in the moderating medium.

p(r)dr= The differential probability that a neutron emitted by a source slows down past the energy E between the radial distances r and r + dr.

q(r,E)= The slowing down density at any radial distance r from the source past the energy E (that is no. of neutrons per unit volume per unit time at any radial distance r from the source slowing down past the energy E per unit time).

and S = The source strength (i.e. no. of neutrons per unit time emitted by the source).

Then

No. of neutrons/time slowing down past the energy E in the differential spherical shell of inner radius r and outer radii r + dr is

= volume of the shell x slowing down density at r past the energy E

$$= 4\pi r^2 q(r,E)dr \qquad \ldots (1)$$

$$p(r)dr = \frac{4\pi r^2 q(r,E)dr}{S} \qquad \ldots (2)$$

Let $\tau(E_o \to E)$ = The neutron age from an energy E_o to a lower energy E

Then it follows from the definition of the neutron age, that

$$\tau(E_o \to E) = \frac{1}{6} \int_0^\infty r^2 p(r)dr \qquad \ldots (3)$$

In order to express the neutron age in terms of the slowing down density, the equation (3) with the help of equation (2) can also be written as

$$\tau(E_o \to E) = \frac{4\pi}{6S} \int_0^\infty r^4 q(r,E)\, dr \qquad \ldots (4)$$

Since the medium is infinite, no neutrons emitted by the source can leak out of the moderating medium and since the medium is non-absorbing, the total no. of neutrons slowing down per unit time past the energy E throughout the moderating medium, at

steady state, must equal the total no. of neutrons emitted per unit time by the source.

Therefore

S = The volume integral of the slowing down density past the energy E over the entire space

or

$$S = \int_0^\infty q\,(r,E)\, 4\,\pi\, r^2\, dr \qquad \ldots (5)$$

Hence eliminating S with the help of Eq. (5), Eq. (4) can be written as

$$\tau\,(E_0 \rightarrow E) = \frac{1}{6}\;\frac{\int_0^\infty r^4\, q\,(r,E)\, dr}{\int_0^\infty r^2\, q\,(r,E)\, dr} \qquad \ldots (6)$$

Equation (6) defines the neutron age from a monoenergetic source of energy E_0 to a lower energy E in terms of the slowing down density past the energy E and forms the basis of other expressions for neutron age which are derived below and are basic to the age measurement technique.

2.2. Neutron Age from an Energy Distributed Source

In actual practice, most of the sources are polyenergetic and hence age determined from such energy distributed source looses its exact definition.

Plutonium - Beryllium neutron source is an energy distributed source having a peak at about 4 Mev.

In this article the meaning of neutron age from such a source spectrum to a final energy E_f in the slowing down region is developed. In such cases measured age depends upon the energy spectrum of the source.

Let

$S(E)\, dE$ = The differential number of neutrons emitted per unit time by the source in the energy intervel E and E + dE

$q(r,E\to E_f)$ = The slowing down density at a radial distance r from the source i.e. no. of neutrons/volume/time, slowing down past the energy E_f arising from a unit point isotropic steady monoenergetic neutron source of energy E put in an infinite non-absorbing moderating medium, at a radial distance r from the source.

$q(r,E_f)$ = The total slowing down density i.e. the total no. of neutrons/volume/time slowing down past the energy E_f at a radial distance r arising from neutrons of all energies above E_f emitted by the energy distributed source.

Then $q(r,E_f)$ can be expressed as in terms of the slowing down kernel $q(r,E\to E_f)$ as

$$q(r,E_f) = \int_{E_f}^{\infty} S(E)\, q(r,E \to E_f)\, dE \qquad \ldots (7)$$

Substituting this value of $q(r,E_f)$ into Eq. (6). The average neutron age to the energy E_f is expressed as

$$\tau(E_f) = \frac{1}{6} \frac{\int_0^\infty \int_{E_f}^\infty r^4 \, S(E) \, q\,(r, E \rightarrow E_f) \, dE \, dr}{\int_0^\infty \int_{E_f}^\infty r^2 \, S(E) \, q\,(r, E \rightarrow E_f) \, dE \, dr} \quad \ldots (8)$$

Since moderating medium is infinite and non-absorbing the volume integral of $q(r, E \rightarrow E_f)$ over entire space must be equal to unity

$$\int_0^\infty 4\,\pi\,r^2 \, q\,(r, E \rightarrow E_f) \, dr = 1 \quad \ldots (9)$$

From Eq. (6) neutron age from an energy E to E_f is

$$\tau(E \rightarrow E_f) = \frac{1}{6} \frac{\int_0^\infty r^4 \, q\,(r, E \rightarrow E_f) \, dr}{\int_0^\infty r^2 \, q\,(r, E \rightarrow E_f) \, dr} \quad \ldots (10)$$

Using Eq.(9), Eq. (10) can be written as

$$\tau\,(E \rightarrow E_f) = \frac{4\pi}{6} \int_0^\infty r^4 \, q\,(r, E \rightarrow E_f) \, dr \quad \ldots (11)$$

Using Eq. (9) Eq. (8) can be written as

$$\tau(E_f) = \frac{4\pi}{6} \frac{\int_0^\infty \int_{E_f}^\infty r^4 \, S(E) \, q\,(r, E \rightarrow E_f) \, dE \, dr}{\int_{E_f}^\infty S(E) \, dE} \quad \ldots (12)$$

Using Eq. (11), Eq. (12) can be written as

$$\tau(E_f) = \frac{\int_{E_f}^{\infty} S(E)\, \tau(E \rightarrow E_f)\, dE}{\int_{E_f}^{\infty} S(E)\, dE} \qquad \ldots (13)$$

The Eq. (13) relates the neutron age from an energy distributed source to the neutron ages from monoenergetic sources, and states that the experimentally measured neutron age from an energy spectrum to the energy E_f is the spectrum weighted average of the neutron ages from monoenergetic sources to the energy E_f over that part of the energy spectrum which is above E_f.

2.3 Foil Activation Technique

In age measurement experiments, the basic quantity to be measured is the neutron slowing down density at certain points in an infinite (as far as possible) non-absorbing bulk of the moderating medium, with a point (as far as practicable) isotropic steady neutron source put at a central location inside the system. In foil activation technique, a foil of a suitable isotope which has a very high and narrow neutron absorption resonance at the energy to which the neutron age is to be measured, is kept at the point

where the neutron slowing down density is to be measured, for a period of time large enough for the foil to become almost fully saturated.

Since at saturation, the activity at the foil, i.e. the rate of decay of product nuclei is equal to the rate of formation by neutron irradiation, the saturated activity of the foil is related to the energy dependent neutron flux as

$$A_s(r) = V \int_0^\infty \phi(r,E)\, \Sigma_a(E)\, dE \qquad \dots (14)$$

where V = Volume of activation foil

$\phi(r,E)$ = The energy dependent neutron flux i.e. the total tracklengths of all neutrons in a unit volume at a radial distance r from the source per unit time per unit energy interval taken at an energy E.

and $\Sigma_a(E)$ = The macroscopic absorption cross-section of the activation foil

In order to be exact the integral on the right side of Eq. (14) has to be evaluated over the entire energy spectrum. But the approximate relation which forms the basis of the foil activation technique is readily obtained from Eq. (14) in the light of the following facts:

(1) The activation foil (Indium in the present case) which is to be used in the experiment should have a very high energy neutron absorption cross-section at the energy (resonance) to which the neutron age is to be measured. Because of this all the activity of the foil would be due to the absorption of neutrons at that particular energy.

(2) The activity due to the absorption of thermal neutrons (for which the absorption cross-section of Indium is large enough to introduce considerable error) is eliminated by putting the activation foils in covers made of cadmium which has a very high neutron absorption cross-section in the thermal region and absorbs practically all the thermal neutrons.

(3) The neutron absorption cross-section of the isotope of which the activation foil is made, in the high energy region is comparatively small and a correction for eliminating the activity induced by neutrons of high energy is applied to the measured activity.

In view of the above facts, it is a very good approximation to assume that practically all the activity of the foil is induced by the neutrons of resonance energy and the Eq. (14) can be approximated as

$$A_s (r) = V \int_{Res} \phi (r,E) \, \Sigma_a (E) \, dE \qquad \ldots (15)$$

The integration over the right side of the Eq. (15) is assumed to be carried out only over the range of the resonance. Since resonance is very narrow, it is a reasonable approximation to assume the energy dependent neutron flux $\phi\ (r,E)$ remains practically constant over this range, hence Eq. (15) can be approximated as

$$A_s\ (r) = V\ \phi\ (r,E_{res}) \int_{res} \Sigma_a\ (E)\ dE \qquad \ldots\ (16)$$

E_{res} = The resonance energy of the isotope of which the activation foil is made.

The integral on the right side of the Eq. (16) is a constant depending only upon the isotope of which the foil is made. Since the foils used are all identical in shape, size and composition and the volume of an activation foil V is a constant of the experiment and hence the Eq. (16) states that

$$A_s\ (r) \propto \phi\ (r,E_{res}) \qquad \ldots\ (17)$$

Fermi age theory gives the following relation between the neutron slowing down density and the energy dependent neutron flux.

$$\phi\ (r,E) = \frac{q\ (r,E)}{E\ \xi\ \Sigma_{sm}(E)} \qquad \ldots\ (18)$$

Where

ξ = The average logarithimic energy decrement of a neutron per collision with the nuclei of the moderating medium surrounding the activation foil.

$\Sigma_{sm}(E)$ = The energy dependent macroscopic scattering cross-section of the moderating medium surrounding the activation foil.

Putting value of ϕ (r,E) from Eq. (18) into Eq. (15), we get

$$\Lambda_s(r) = V \frac{q(r,E)}{E\,\xi\,\Sigma_{sm}(E)} \int_{res} \Sigma_a(E)\, dE \qquad \ldots (19)$$

The integeral on the right side of Eq. (19) depends only upon the isotope of which the activation foil is made and hence it is a constant as far as the experiment is concerned. Foils used in the experiments are all identical in shape, size and composition so that the volume of the activation foil V is also a constant of the experiment. Since ξ and Σ_{sm} do not vary rapidly with respect to E, the Eq. (19) can be written as

$$\Lambda_s(r) \propto q\,(r,E_{res}) \qquad \ldots (20)$$

Equations (17) and (20) can be combined to give

$$\phi\,(r,E_{res}) \propto \Lambda_s(r) \propto q\,(r,E_{res}) \qquad \ldots (21)$$

Equation (21) is applicable only in asymptotic region.

Since the foils used in an experiment are of finite size, both the sides of the foils are not activated equally. The activation on each side is proportional to the flux of only those neutrons which have a velocity component directed into the foil from that side. Because of the finite size of the foil there will be neutron absorption in the foil itself (self absorption) so that the flux on one side is not the same as that on the other side of the foil. However, for the purpose of the experiment we assume that the flux at the point where the foil is located (center of the foil) is taken to be the average of the fluxes on the two sides of the foil. Since the fluxes are proportional to the activities on the two sides of the foil, namely $A_{s1}(r)$ & $A_{s2}(r)$, we can write

$$\phi\ (r,E_{res}) \propto A_{s1}\ (r) + A_{s2}\ (r) \propto q\ (r,E_{res}) \qquad \ldots\ (22)$$

Equation (22) states that the total saturation activity of an activation foil is directly proportional to the neutron flux or the slowing down density at the location of the foil and is basic to the foil activation technique.

With the help of Eq. (22), Eq. (6) can be rewritten as

$$\tau = \frac{1}{6} \quad \frac{\int_0^\infty r^4\ A_s(r)\ dr}{\int_0^\infty r^2\ A_s(r)\ dr} \qquad \ldots\ (2\ )$$

where $A_s(r)$ = is the total saturation activity of the activation foil kept at a radial distance r from the neutron source.

or

$$A_s(r) \propto A_{s1}(r) + A_{s2}(r) \qquad \ldots (24)$$

Equation (23) expresses the neutron age in terms of the total saturation activity and is used in the calculation of neutron age in a foil activation experiment.

2.4 Activation Analysis

In a foil activation experiment, the basic quantity to be calculated is the saturation activity after the foil has been irradiated for a period of time large enough for the foil to become almost fully saturated.

The activated foil is taken out of the moderating medium and allowed to decay. During its decay it emits radioactive particles which can be counted by a counter for a preset period of time. The saturated activity of each side of an activated foil is calculated from the total number of counts registered by a counter. In this article an expression is developed for the saturated activity of a certain side of an activated

foil kept at a certain point in the moderating medium in terms of the total number of counts obtained from the counter in a certain period of time.

Analysis During Irradiation

Let $N(t)$ = Number of product nuclei formed due to irradiation into the moderating medium at any time t.

λ = Decay constant of product nuclei

Rate of increase in number of product nuclei

= Rate of their formation due to irradiation

− Rate of radi[illegible].

At saturation there is an equilibrium between rate of formation due to irradiation and rate of radi[illegible] decay. The rate of formation due to irradiation is equal to saturation activity A_s. Hence rate of increase in number of product nuclei during irradiation is given by

$$\frac{dN}{dt} = A_s - \lambda N \qquad \ldots (25)$$

Initial condition is

$$N(0) = 0 \qquad \ldots (26)$$

Solution of Eq.(26) and (27) is

$$N = A_s (1 - e^{-\lambda t}) \qquad \ldots (27)$$

Left side of Eq. (28) is the activity at any time t after the foil is put into the moderating medium. The activity builds up exponentially and tends to reach the value A_s asymptotically. In a period of about 10 half lives of the product isotope the activity attained is more than 99% of the value at the saturation activity and the foil is supposed to be almost fully saturated.

Analysis After Irradiation

Let $N(t)$ = Number of product nuclei at any time t after the foil is taken out of the moderating medium.

and N_o = Initial number of product nuclei at saturation.

After the foil is taken out, the product isotope undergoes exponential radioactive decay and the number of product nuclei at any time t is given by the equation

$$N = N_o e^{-\lambda t} \qquad \ldots (28)$$

The number of product nuclei that undergoes radioactive decay in the interval of time between the instant t_i and t_f.

= Number of product nuclei at time t_i - Number of product nuclei at time t_f

$$= N_o \left(e^{-\lambda t_i} - e^{-\lambda t_f}\right) \qquad \ldots (29)$$

Let η = Counter efficiency

C = Total number of counts obtained in the interval of time between t_i and t_f.

B = The background counts in an equal interval of time

Equation(29) can be written as

$$C - B = \eta\ N_o\ (e^{-\lambda t_i} - e^{-\lambda t_f}) \qquad \ldots (30)$$

The saturation activity of the side of the foil which is counted can be expressed in terms of the total counts C and the background B, using Eq. (30) as

$$A_s = \eta\ N_o = \frac{\lambda (C - B)}{\eta (e^{-\lambda t_i} - e^{-\lambda t_f})} \qquad \ldots (31)$$

Let t_c = Counting time (same for each side)

and

t_1, t_2 = The instants at which the counting of the 1st and 2nd side respectively are started.

Using the subscripts 1 and 2 refer the two sides of an activation foil, the saturation activities of the 1st and 2nd side of the foil can be written as

$$A_{s1} = \frac{\lambda (C_1 - B)}{\eta\ (e^{-\lambda t_1} - e^{-\lambda (t_1 + t_c)})} \qquad \ldots (32)$$

$$A_{s2} = \frac{\lambda(C_2 - B)}{\eta(e^{-\lambda t_2} - e^{-\lambda(t_2+t_c)})} \qquad \ldots (33)$$

Hence combining Eq. (24), (32) and (33) the total saturation activity can be written as

$$A_s = \frac{\lambda}{\eta}\left[\frac{C_1 - B_1}{e^{-\lambda t_1} - e^{-\lambda(t_1+t_c)}} + \frac{C_2 - B}{e^{-\lambda t_2} + e^{-\lambda(t_2+t_c)}}\right] \qquad \ldots (34)$$

Since the counting efficiency η is maintained constant throughout an activation experiment for neutron age measurement, and the decay constant λ is constant depending upon the isotope of which the activation foil is made, the Eq. (35) can be simplified to

$$A_s \propto \left[\frac{C_1 - B_1}{e^{-\lambda t_1} - e^{-\lambda(t_1+t_c)}} + \frac{C_2 - B_2}{e^{-\lambda t_2} - e^{-\lambda(t_2+t_c)}}\right] \qquad \ldots (35)$$

Equation(35) gives a number proportional to the total saturation activity of the foil in terms of the directly observable quantities which are measured in a foil activation experiment.

2.5 Neutron Induced Activities of Indium

Activation foils made of natural Indium containing 95.77 percent of In^{115} and 4.23 percent of In^{113} are used in the experiment. Due to neutron irradiation both In^{115} and In^{113} are converted into radioactive isotopes. The neutron induced reactions and the decay modes of the product isotopes are given below.

In^{113} Activities

(1) $In^{113} + n \longrightarrow In^{113m} + n$, $In^{113m} \xrightarrow{104min.} In^{113}$ (STABLE)

(2) $In^{113} + n \longrightarrow In^{114} \xrightarrow{72sec.} Sn^{114}$ (STABLE)

(3) $In^{113} + n \longrightarrow In^{114m} \xrightarrow{49days} In^{114} \xrightarrow{72sec.} Sn^{114}$ (STABLE)

In^{115} Activities

(4) $In^{115} + n \longrightarrow In^{115m} + n$; $In^{115m} \xrightarrow{4.5hr.} In^{115}$ (STABLE)

(5) $In^{115} + n \longrightarrow In^{116} \xrightarrow{13.4sec.} Sn^{116}$ (STABLE)

(6) $In^{115} + n \longrightarrow In^{116m} \xrightarrow{54min.} Sn^{116}$ (STABLE)

Since in a foil activation experiment on neutron age to In resonance the foils are counted after waiting for a measured period of about 10 minutes, the activities (2) and (5) are almost fully eliminated due to their very short half lives. Also the activity (2) is very small due to the small percentage of In^{113} in the activation foil. Thus no correction is applied to the measured activity in order to eliminate these two activities.

The activities (1), (3) and (4) are mainly due to high energy neutrons for which the activation cross-section is very small compared to the activation cross-section for the 54 minutes main activity which is mainly due to the resonance neutrons. The activities (1) and (3) are very small because of small percentage of In^{113} in the activation foil. Since the foils are irradiated for about 8 hours the 49 day activity builds up only to a very small fraction of its saturation value. Therefore no correction is applied to the measured activity in order to eliminate these high energy activities. Of-course a correction is applied to the measured activity for eliminating that part of the 54 minute activity which is due to high energy neutrons, in order to get the activity induced only by the neutrons of resonance energy. It is assumed

that almost all the counts obtained from an Indium foil, 10 minutes after it is taken out of the moderating medium, are due to the 54 minute activity of In^{115} decaying into Sn^{116}. Thus the value of the decay constant λ in Eq. (36) for calculating the measured activity from the counts obtained is calculated from this half life.

CHAPTER III

EXPERIMENTAL SET - UP AND PROCEDURE

3.1 Description of the Set-up

In this experiment the main equipment and accessories used are

1. Compressor, moisture absorber and filter to get the purified air in the compressed form

2. A pressure regulator value, a pressure gauge and rotameters to supply the required amount of air through the system

3. A tank for the moderator

4. An arrangement to create air bubbles in the desired fashion

5. Neutron source and its holder

6. Activation foils and an arrangement for suspending them

7. A Beta counting set up

The detailed description is given below.

Compressor:

The required amount of purified air is obtained from a reciprocating compressor shown in the photograph

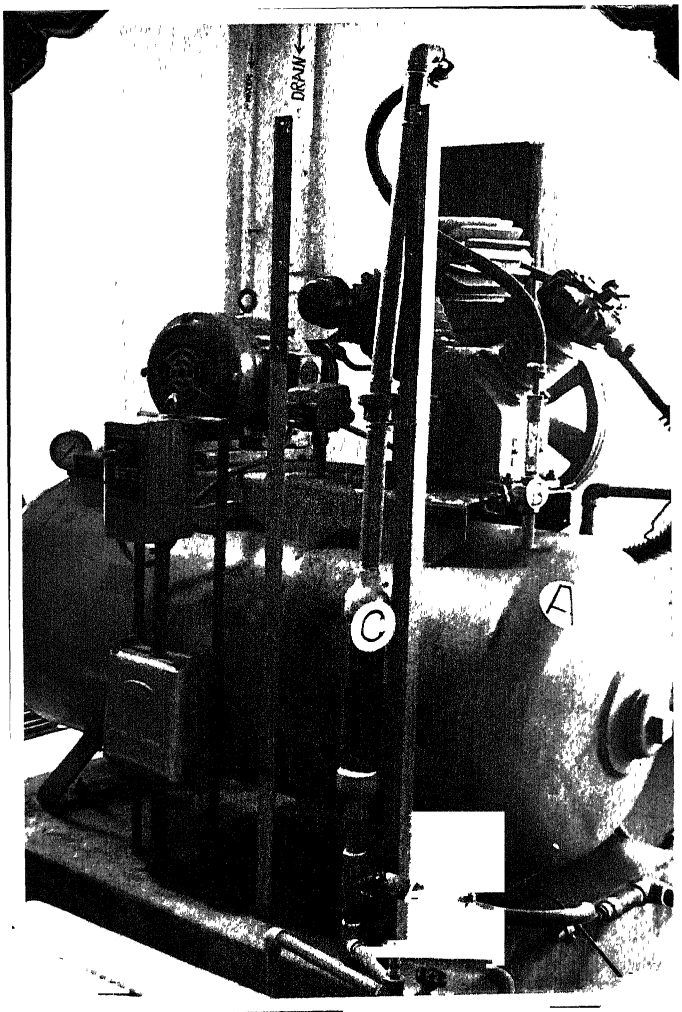


FIGURE 1 Photograph of Compressor Unit

(Fig.1)having the following specifications (No. of stages 2, Displacement 11 C.F.M., W.P. 170 psi, Motor H.P. 3). The air from the compressor is passed through a moisture absorber C and filter E (Figure 2). The purified air at the desired pressure can be supplied to the tank with the help of a pressure regulator value D and pressure gauge F.

Arrangement to Regulate the Supply of Air

The output of the pressure regulator value D is distributed into six lines with the help of plastic tees, crosses and Teflon tubes. Each line is connected through a control value to a rotameter. Six rotameters and control valves are fitted on a board. A photograph of this arrangement is shown in Figure 2. Figure 3 is a line diagram of the complete set up for the supply of air. With the help of these six flow control values, the desired flow rate can be obtained from each of the rotameter. The rotameters have been calibrated with Wet test precision meter. Their calibration curves have been shown in Figures 17 to 22.

Aluminium Tank with Pure Water

The moderating medium in which the neutron age was determined viz. a two phase system consisting of

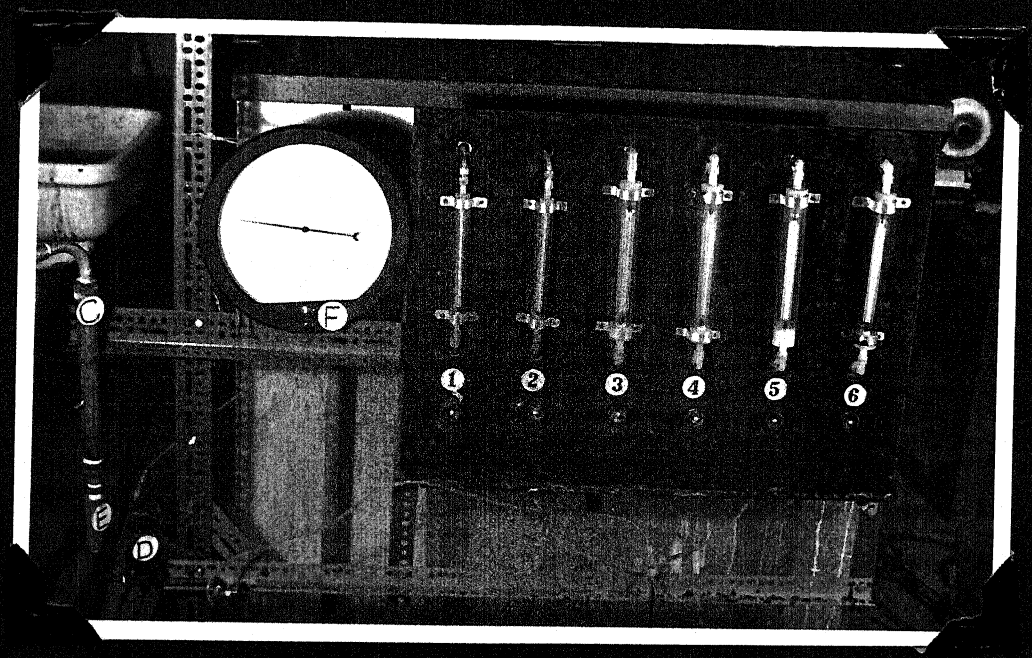


FIGURE 2 Photograph of Air Flow Control Panel

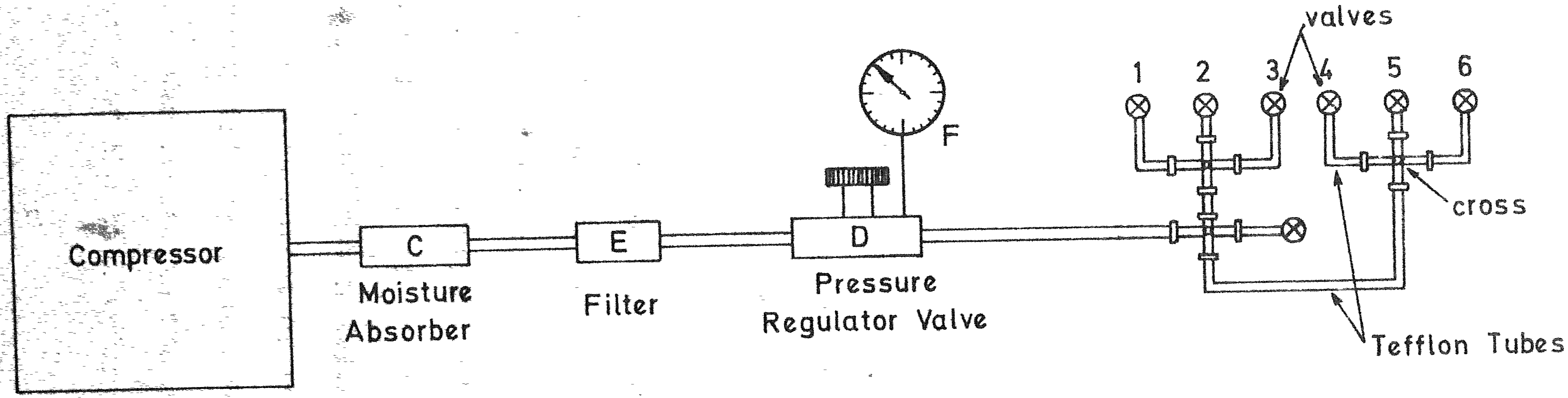


FIGURE 3 Line Diagram of Air Flow Circuit

air bubbles and light water was contained in an aluminium tank having inside dimensions 120.5 cm. x 120.5 cm. x 120.5 cm and fabricated from 6.35 mm. thick aluminium plates.

Aluminium was used mainly to overcome the troubles due to corrosion and radioactivity that the tank might acquire due to long exposure to neutrons during the experiment if other common materials are used. The contamination by dust etc. of the moderating medium in the tank was prevented by covering the tank with a cover fabricated from aluminium sheet on a mild steel frame, with a soft rubber gasket.

Fifteen hundred litres of pure water was filled in the tank to get the required hetrogeneous mixture of air and light water. Tap water had a conductivity of about 1000 micromhos/cm (10) and so it required a considerable amount of treatment. For obtaining light water a four column I.A.E.C. demineraliser plant was utilised. The output of the demineraliser plant has a conductivity of 5 micromhos/cm. This demineralised water was stored in the aluminium tank. The conductivity of the tank water was measured daily

during the experiment. The average conductivity of the tank water during the experiment was found to be 9 micromhos/cm.

Arrangement for Creating Air Bubbles

In the aluminium tank six sets of 'U' tubes fabricated as shown in Figures 4 and 5 are suspended. The outlet of each rotameter is connected to both the upper ends of 'U' tube by means of plastic Tees and Teflon tubes as shown in Figure 6 and Figure 7. The 'U' tube consists of two vertical 3/8'' I.D. aluminium tubes threaded at both ends. The upper threaded end receives a pair of brass nuts meant for suspension and adjustment. The lower threaded end receives an aluminium plug. Two such plugs are press fitted into 1/2'' I.D. aluminium tube, having 21 equally spaced holes of .0605'' diameter drilled along a line. The axis of the holes are at right angles to the axis of the tube.

Air enters from both ends of the 'U' tube and comes out of the .0605'' holes in the form of bubbles travelling upwards.

This arrangement has been specially designed in order to ensure uniform flow of air out of the .0605'' diameter holes.

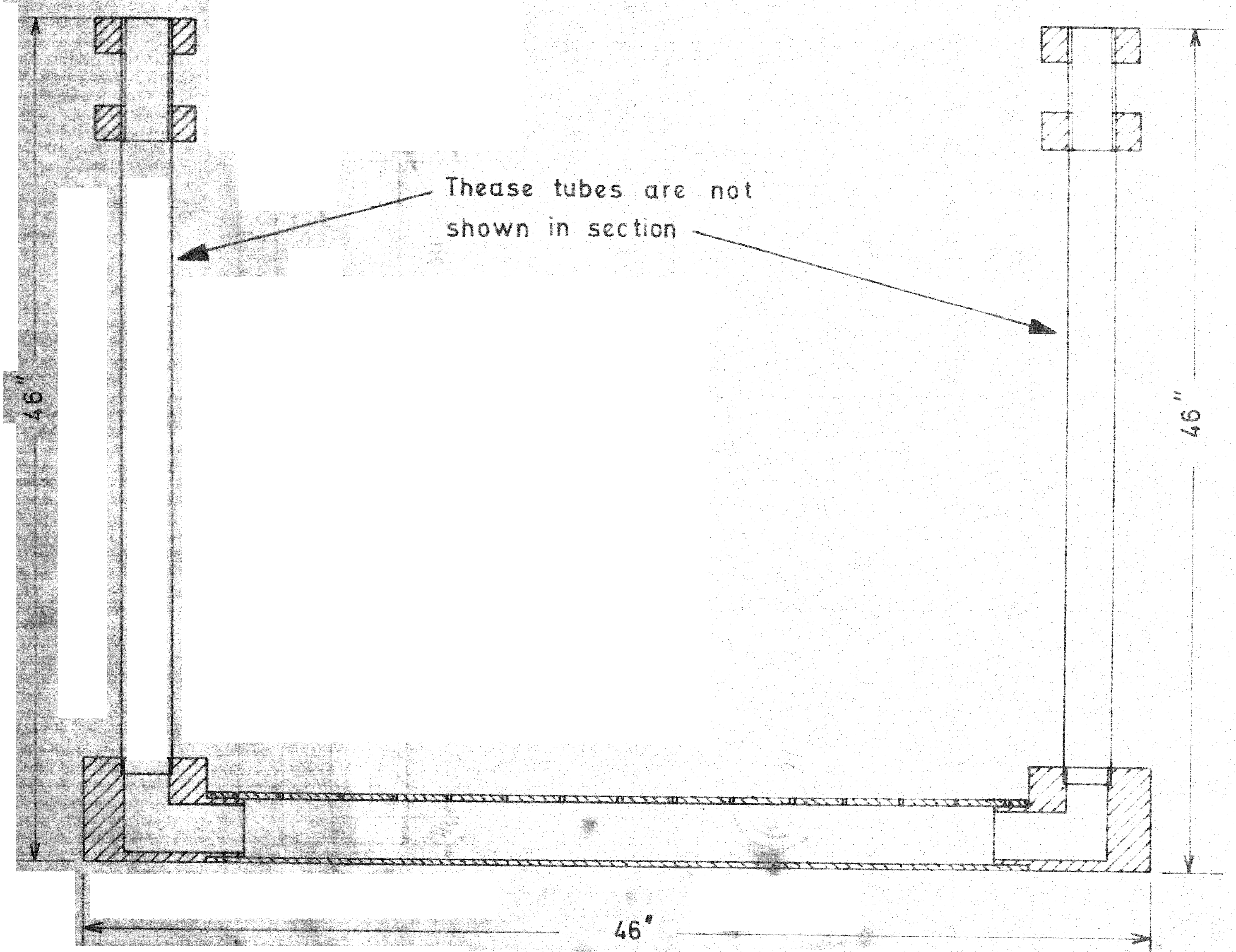


FIGURE 4 'U' TUBE (six such sets)

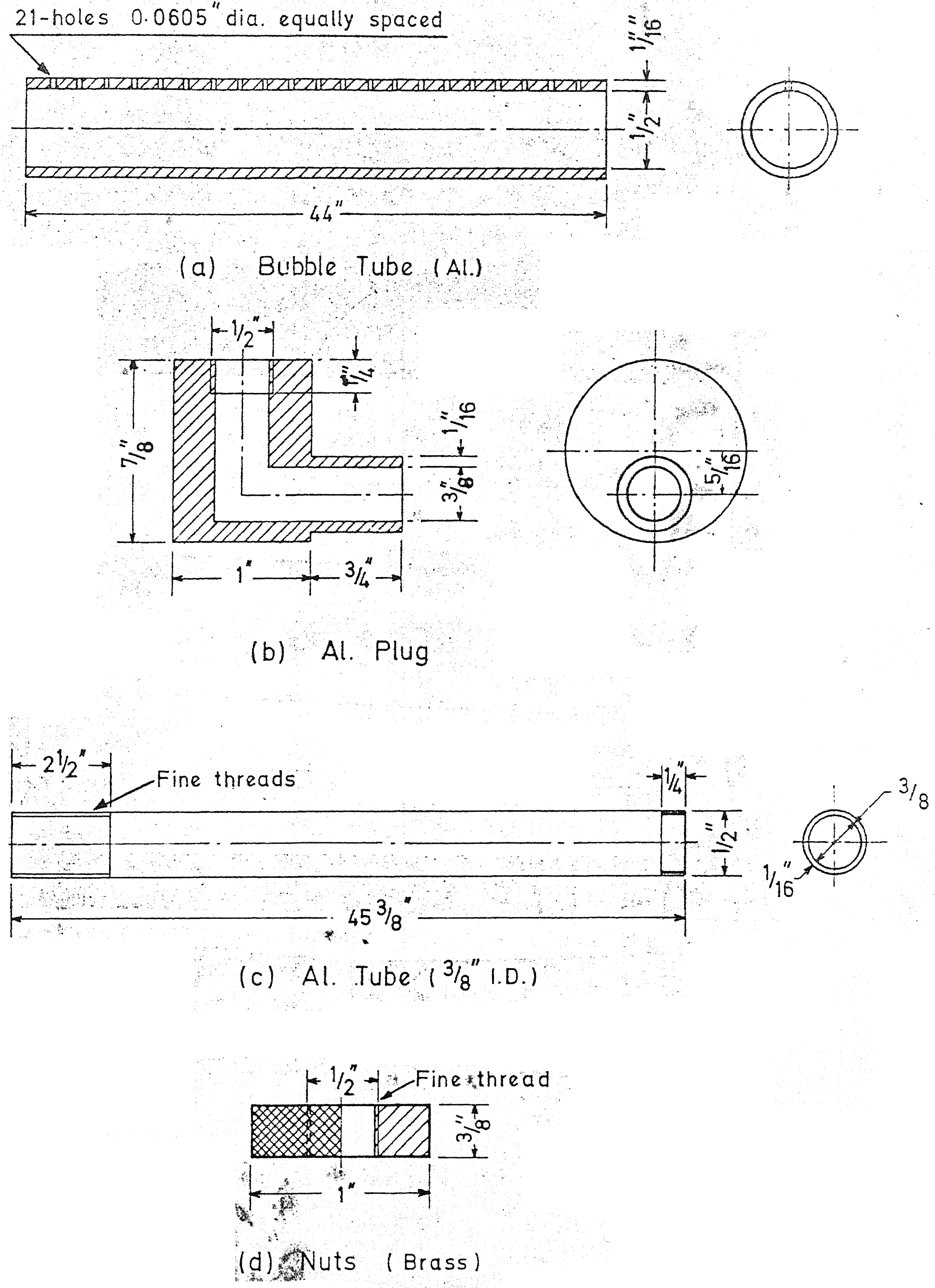


FIGURE 5 Details of U Tube

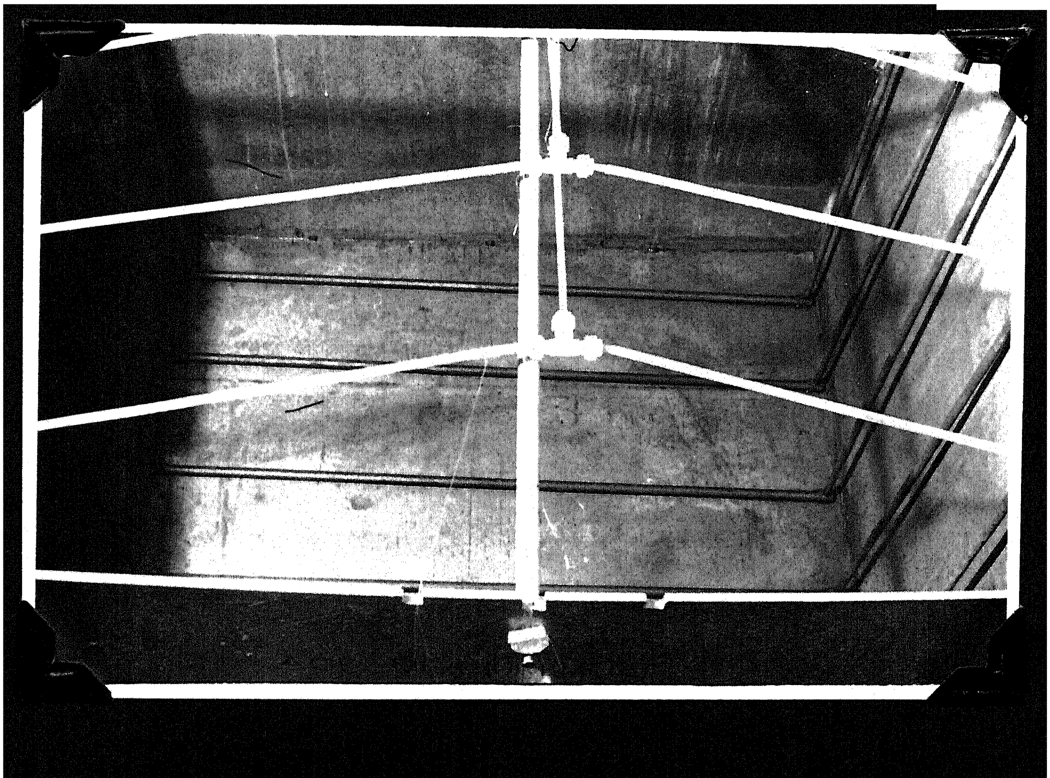


FIGURE 6 Photograph of U Tube Inside the Tank

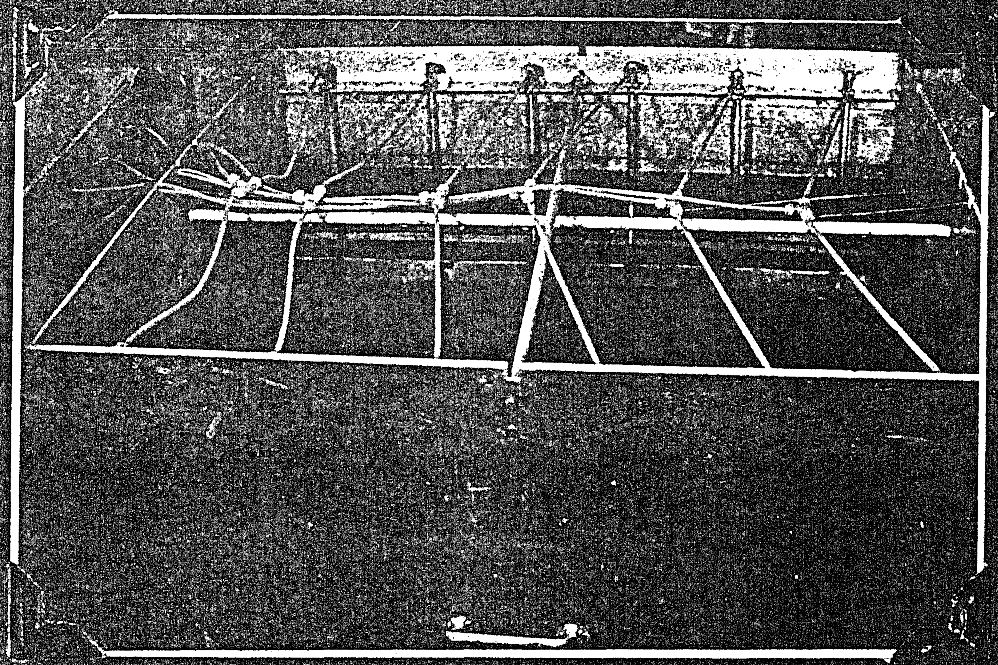


FIGURE 7 Photograph of Top View of Tank

Trials were first made by placing the 1/2" I.D. tube with .0605" holes on the base of the tank. It was observed that air comes out of few holes only. Realising that the flow of air out of the holes was dependent on the inclination of the axis of the tubes to the horizontal plane an adjustable suspending arrangement described above was used for each tube. For the same reason air was introduced at both the ends of the tube.

Further, to ensure that all the holes of the six sets of U tubes give out a uniform amount of air in the form of bubbles, the total air supply from the pressure regulator valve was distributed to six lines each having a control valve and a rotameter of its own. Trials were first made with a single header feeding all the six 'U' tubes which did not work and therefore the above mentioned arrangement was devised.

<u>Neutron Source</u>

A 5 Curie Plutonium - Beryllium neutron source emitting about 8 x 10^6 neutrons/sec. procured from the Bhabha Atomic Research Center, Trombay was used in the experiment. The Plutonium - Beryllium intermetallic compound was jacketed in a steel cylinder cover of diameter 5.3 cm. and height 7.3 cm. As the steel cylinder cover had no holding device, it was put in a

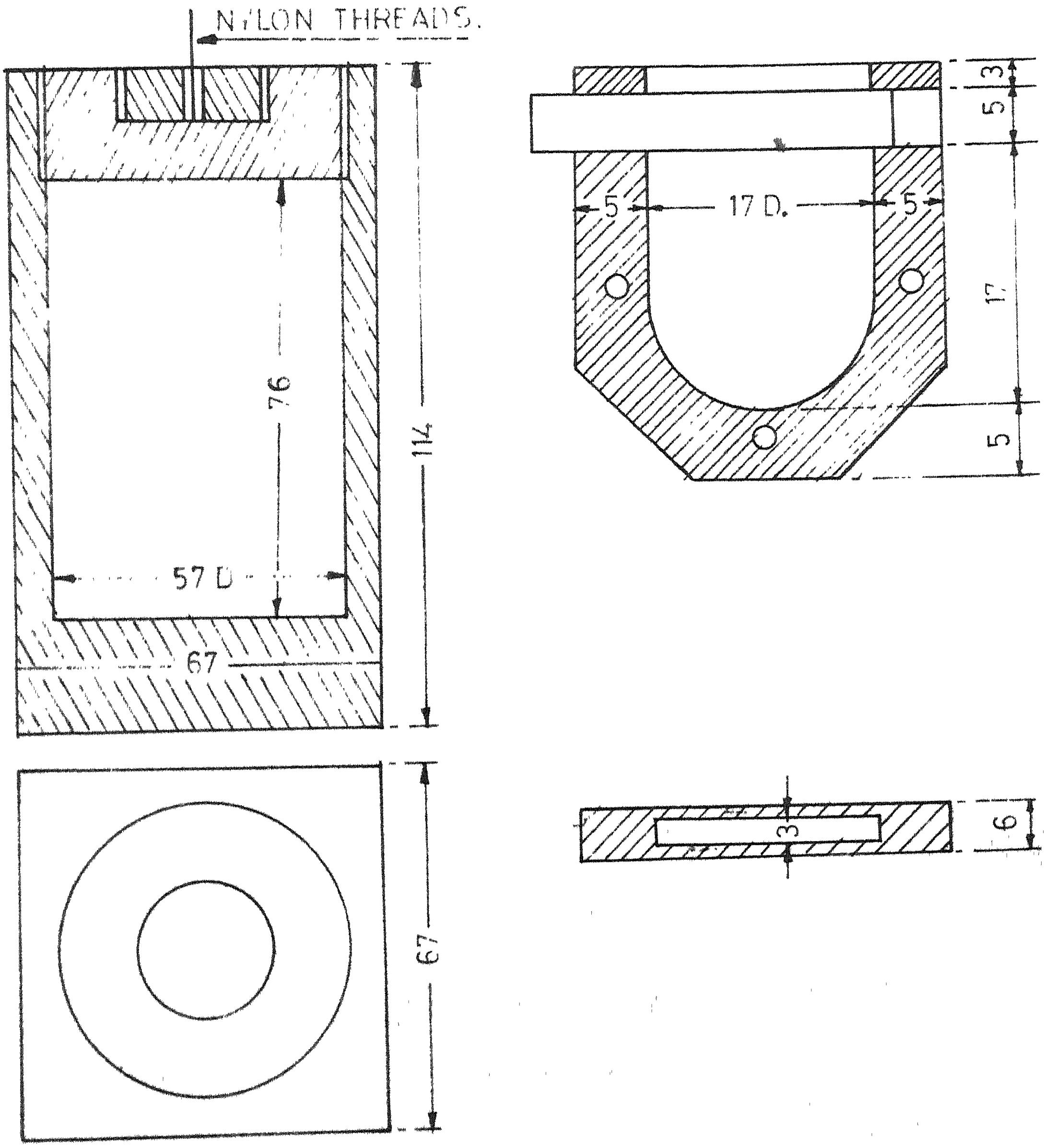
rectangular source container (Figure 8 a) made of perspex, and was suspended by a nylon thread in the tank.

Plutonium - Beryllium neutron source is an energy distributed source having a characteristic energy spectrum (11) (Figure 9) ranging from roughly zero to about 10.6 Mev. with an average neutron energy of about 4.2 Mev. (12) . Since the half life of Plutonium is 24,300 years, it is reasonable to assume that the source remains steady during the few days of the experiment.

Activation Foils

The activation foils used in the experiment were made of pure Indium containing 95.77 percent of In^{115} and 4.23 percent of In^{113}. and were 12.7 mm. diameter and .254 mm. thick. Cadmium cover Indium foils were put inside the perspex foil holders (Figure 8b) which were suspended inside the tank containing water by nylon threads. Two horizontal foil suspension rods of 2 cm. diameter and 115 cm. long were fixed at the top of the tank and perpendicular to each other.

The foil holders were made of perspex in order to minimise the flux perturbation caused by introducing another material in the moderating medium.



(a) SOURCE HOLDER.

(b) FOIL HOLDER.

FIG. 8

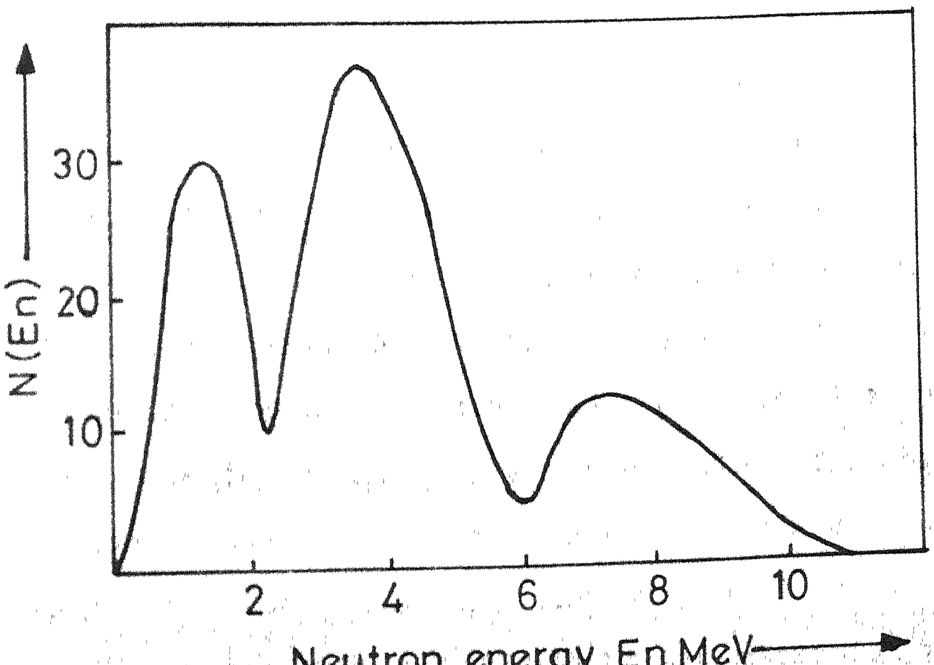


FIG. 9. PU-BE SPECTRUM.

The flux perturbation will be minimum if the moderating ratio of the foreign material introduced into the moderator is of the same order as that of the moderator. The moderating ratio of the perspex is 153.6 and that of light water is 147.0 and hence the flux perturbation was negligible.

The foil holders containing the activation foil were suspended through the holes drilled in the suspension rods. The foil holders were kept in position by small lead weights suspended at the bottom of the foil holders by nylon threads. The center of the neutron source and the activation foils were all in a horizontal plane 60 cm. below the axis of the foil suspension rods. This distance was marked on a nylon thread with the help of a meter scale. The marks on nylon threads were checked several times by several persons. The foils were also suspended by nylon threads whose distances from the axis of the aluminium rod were also marked by the meter scale and marks were made at 60 cm. distance from the center of the foil. It was noted that distances were within $\pm$ 1 mm.

Beta Counting Set Up

A photograph of the Geiger Muller counting set-up used in the experiment is shown in Figure 10. The

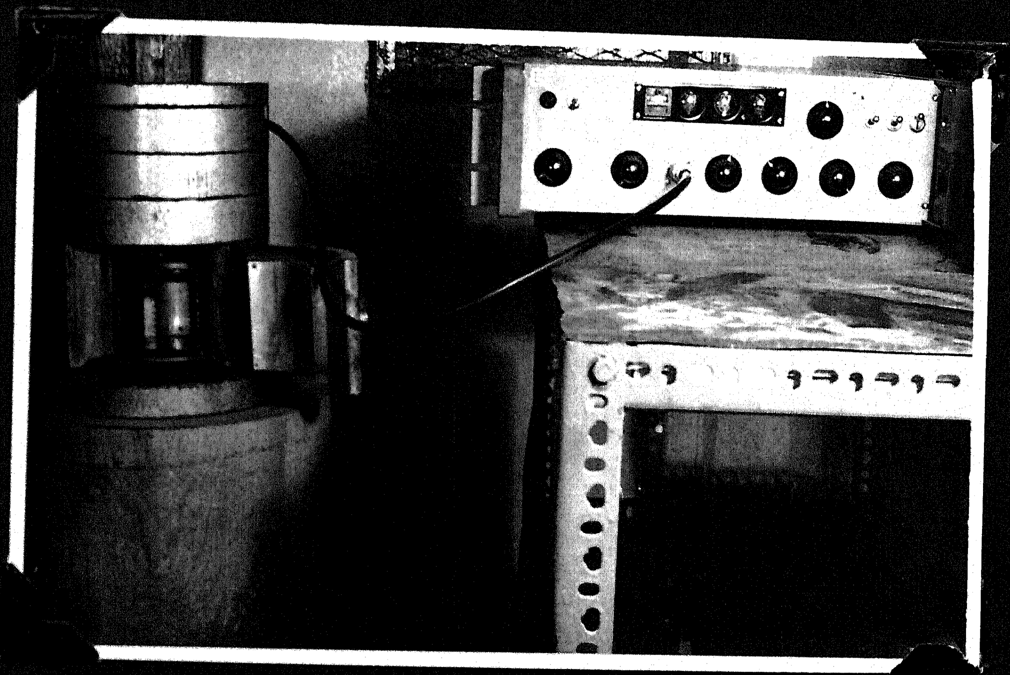


FIGURE 10 Photograph of Geiger Counter

plateus of four G.M. tubes were plotted and a G.M. tube having a good plateu as shown in Figure 11 was used for the experiment. The change in count rate per 100 volt was 5 preset. The operating voltage selected was 1380 volts. A counting time of 10 minutes was set with the help of a preseut counter. The G.M. tube with the foil rack was kept inside a lead castle in order to reduce the background count rate of the counting system.

3.2 Procedure of the Experiment

The source was suspended at the centre of the tank and the foils were suspended at the same depth as the source. At a time only eight foils in one direction, 4 on either side of the source were used in order to keep a minimum distance of 10 cms. between any pair of foils, which is required to eliminate the shadowing effect of one foil on another. The experiment was repeated a number of times, each time with only 8 foils in one direction but with changed spacing so as to cover the whole range from 5 cm. to 50 cm. from the source with a spacing of 2 cm. upto 15 cm. from the source and a spacing of 5 cm. beyond.

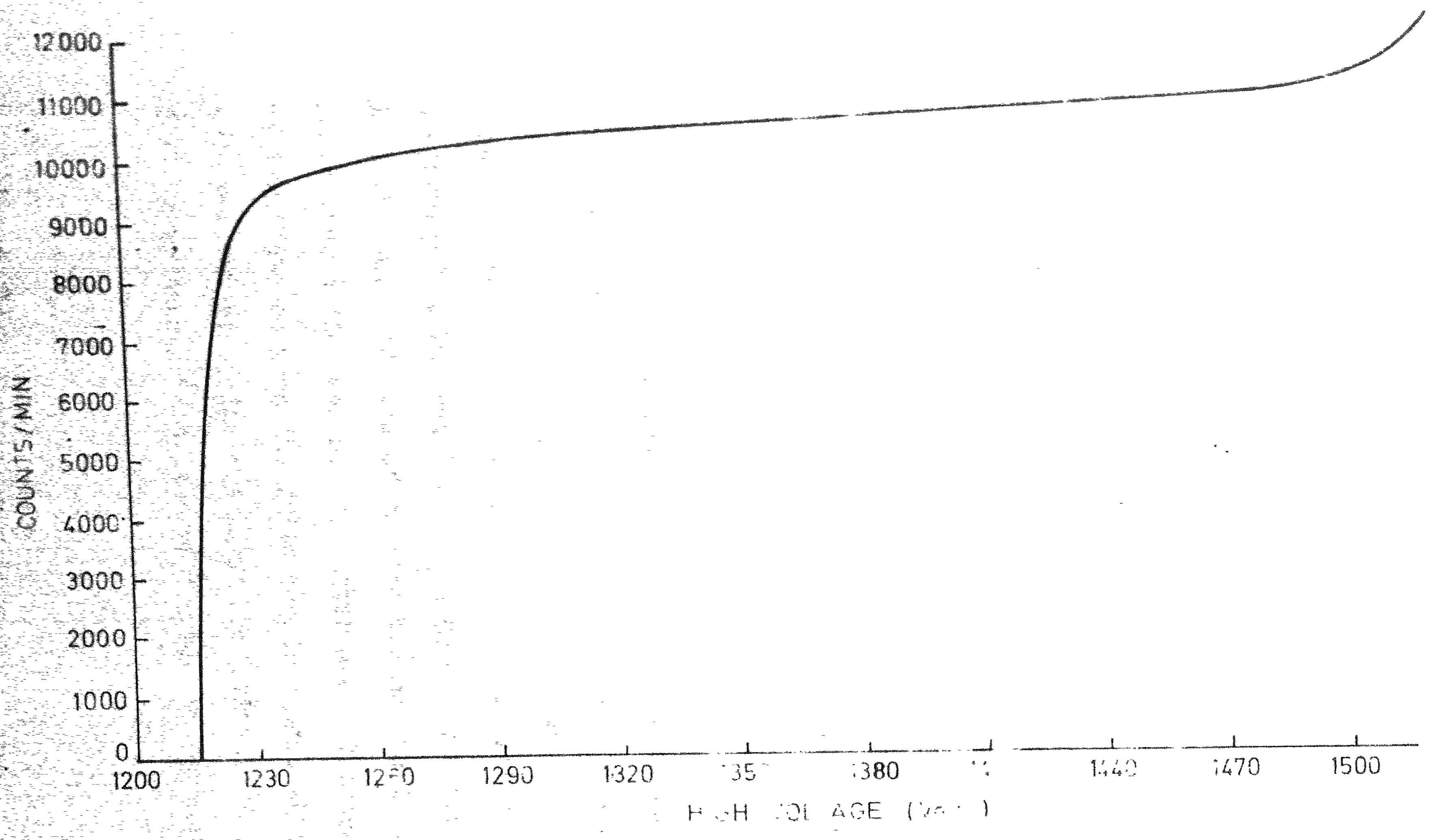


FIG.11 PLATEU CURVE FOR G.M. COUNTING

The measurements were made in a direction parallel to the axis of the bubble tube as well as perpendicular to it in a horizontal plane at the same height as the center of the source, for air flow rate of 18000 cc/min. The neutron age for the air flow rate of 18000 cc/min. in the two mutually perpendicular directions was found to be 67.18 $\pm$ 3.28 and 68.79 $\pm$ 3.57 respectively (Table 18). This revealed that there is no appreciable difference in the age values in the two mutually perpendicular direction. Therefore for the other two air flow rates of 36000 cc/min. and 54000 cc/min. measurements were made only in a direction perpendicular to the axis of the bubble tube.

First the foils were fixed at the desired position in the tank. Next air flow rate was adjusted at the required rate by adjusting the pressure regulator valve and flow control values. After this, the source was lowered into the tank and was fixed in position. The time of putting the source in the moderating medium was noted. After about 7 hours of irradiation, when the foils acquired more than 99.9 percent of their saturation activities, the foils were taken out of the medium one by one and

their activity was counted. The instant at which the foils were taken out was noted and a stop watch was started exactly at the instant. The first side of the foil was counted exactly after 10 minutes waiting time (to avoid 13.4 sec. and 72 sec. activity) for ten minutes with the G.M. counting set-up. Then the second side of the foil was also counted for 10 minutes. In this way all the activated foils were counted. Waiting time for the first side as well as for the second side was noted accurately to .5 sec. with the help of a stop watch, whereas counting time was fixed with the help of the preset counter. The background was noted for 10 minutes just before counting the first side and just after counting the second side of every foil. In this fashion the activity of all the foils were counted. The same foils were not used for the next experiment. While the foils were irradiated, care was taken to see that the flow rate did not change.

In each experiment the counter was first calibrated with the help of a standard β source also kept in the shelf No. 3 of the foil rack. After the calibration, this standard β source was replaced by the activated foils one at a time to count their activity.

CHAPTER IV

CALCULATIONS, RESULTS AND DISCUSSION

4.1 Errors and C

The saturated activities at various distances from the source are calculated by using Eqs. (32) and (33). When an activated foil is counted, due to background counts the number of counts registered are higher then the actual number of counts, hence a correction is applied to the total number of counts observed from the activated foil.

Since Indium has a finite activation cross-section for neutrons of energies higher than the resonance energy, a fraction of the saturation activity of cadmium - covered Indium foils, though small, is induced by the high energy neutrons. Hence a correction is applied to eliminate the high energy contribution.

The neutron source and the activation foils are both of finite sizes. For calculation of the neutron age, we need the activity at specified points. Hence a correction is applied to the measured saturated activity to correct for the finite size. The details of the method of calculations are as follows

Background Correction

The background is observed before and after counting the foil. The average of the two count rates are subtracted from the actual number of counts. The background is noted for a period of time equal to the counting time of the foil.

Corrections for High Energy Activation (13)

In order to correct for high energy activation, a single cadmium covered Indium foil and a cadmium covered sandwich of three similar Indium foils are activated at the same point in the medium. The saturated activity of a single cadmium covered Indium foil is due to the neutrons of both the resonance energy and high energy. The neutrons of thermal energies are absorbed by the cadmium cover itself. The saturation activity, of the interior indium foil of the cadmium covered sandwich is due only to the high energy neutrons since most of the indium resonance (1.46 ev.) neutrons are absorbed by the outer indium foils of the sandwich. Therefore in order to obtain the saturated activity induced by the neutrons of the resonance energy, the saturation activity of the innermost indium foil is subtracted from the activity of a single cadmium - covered indium foil. This is given by:

$$A_s \text{ (resonance)} = A_s \text{ (cd-Covered)} - A_s \text{ ((cd+In)-covered)}.$$

Corrections for Finite Sizes of Source and Foil (14) & (15)

The saturated activities corrected for background and high energy activation are corrected for the finite sizes of the neutron source and the activation foil by the approximate formula,

$$A_s(r) = A_m(r) - \frac{K}{r}\frac{dA}{dr} \qquad \ldots(36)$$

where $$K = \frac{x^2 + y^2 + 6a^2}{24}$$

$A_s(r)$ = The saturation activity corrected for the finite sizes of the source and the foil.

$A_m(r)$ = The measured saturation activity.

x ,y = The length and diameter of the source.

a = The radius of the activation foil.

This formula assumes a uniform distribution of the total strength of the neutron source over the projected area of the source on a plane passing through its centre and parallel to the face of the activation foil.

4.2 Calculations and Results

The saturated activity induced by resonance neutrons as well as the second moment and fourth moment of the activities viz. $r^2 A_s(r)$, $r^4 A_s(r)$

respectively have been calculated. The plot of $r^2 A_s(r)$ Vs r and $r^4 A_s(r)$ Vs. r on semi-log paper (Figure 12 to Figure 15) is obtained. The point at which the curve $\ln (r^2 A_s(r))$ Vs. r becomes a straight line is noted. The areas under the second moment curve and the fourth moment curves from r = 0 to r = 24 cm. are calculated numerically using the Simpson's rule

The areas under the second moment curve and the fourth moment curve from the point where the curve $\ln (r^2 A_s(r))$ against r becomes straight to $r = \infty$ are calculated analytically using the fact that the slowing down density or the flux can be assumed to have an asymptotic distribution given by

$$\phi(r) = \frac{a\, e^{br}}{r^2} \quad \text{(b is negative)} \qquad \ldots (37)$$

or

$$A_s(r) = \frac{a\, e^{br}}{r^2} \qquad \ldots (38)$$

The above equations can be written as

$$\ln (r^2 A_s(r)) = \ln a + br \qquad \ldots (39)$$

hence the plot of $\ln (r^2 A_s(r))$ against r is a straight line.

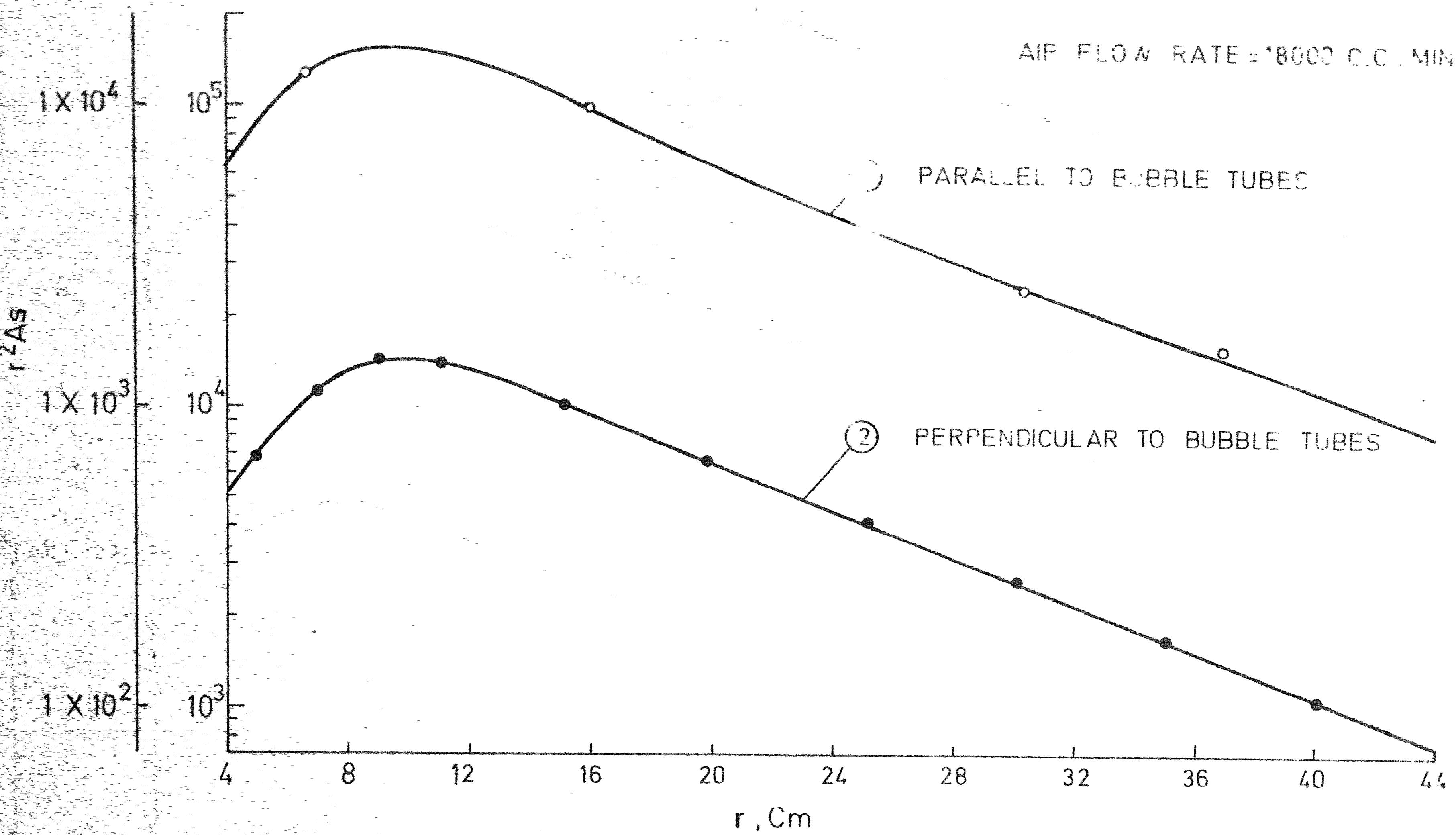


FIG.12. GRAPH OF r^2As Vs. r FOR DATA OBTAINED WITH INDIUM FOILS FOR NEUTRONS PRODUCED BY PLUNIUM-BERRLLIUM SOURCES

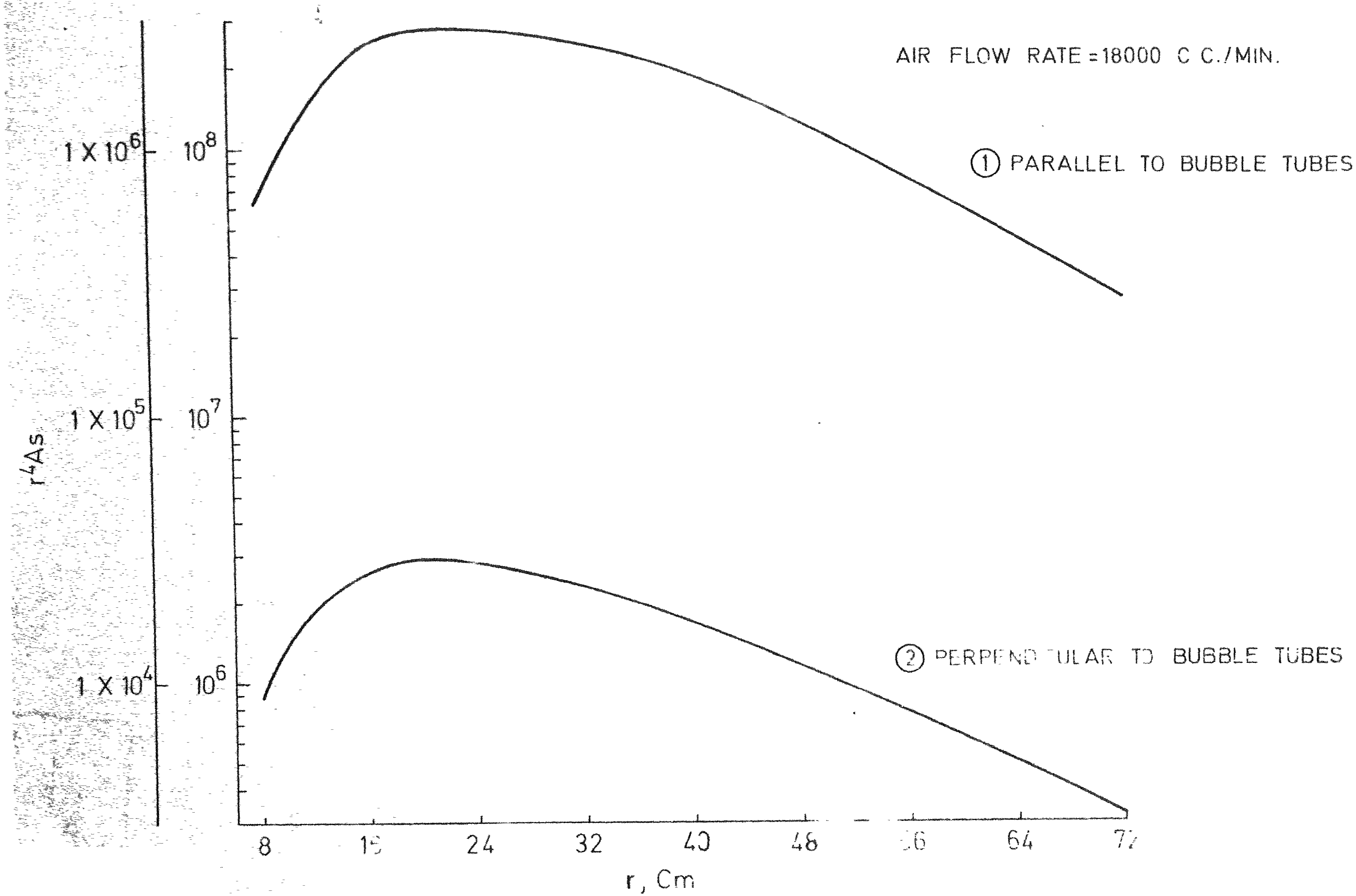


FIG. 14. GRAPH OF r^4As Vs. r DATA OBTAINED WITH INDIUM FOILS FOR NEUTRONS PRODUCED BY PLUTONIUM-BERYLLIUM SOURCES

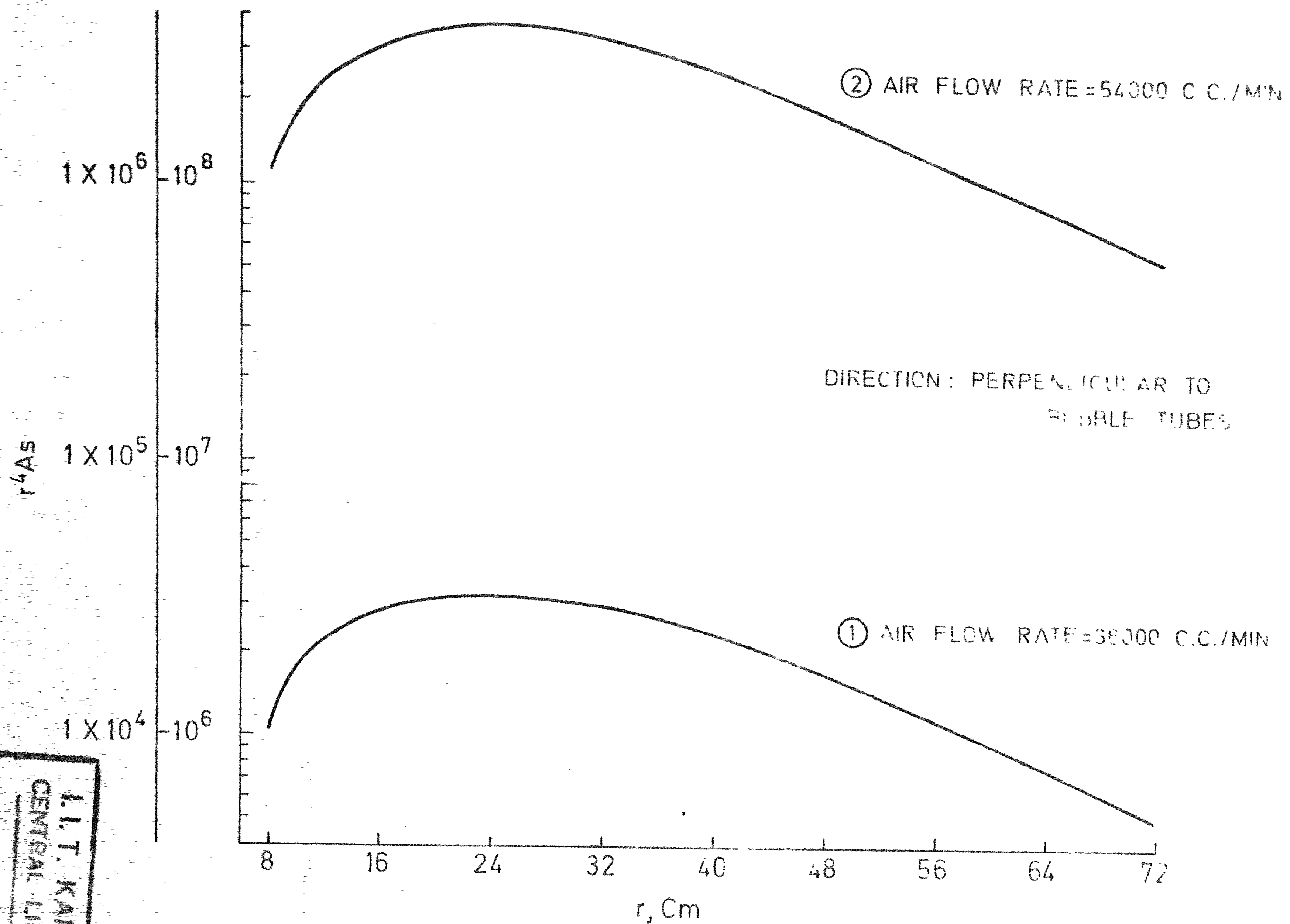


FIG.15 GRAPH OF r^4As Vs r FOR DATA OBTAINED WITH INDIUM FOILS FOR NEUTRONS PRODUCED BY PLUTONIUM-BERYLLIUM SOURCES

The values of constants a and b are determined by fitting a least square straight line over the fairly straight portion of the plot of $\ln (r^2 A_s(r))$ against r obtained from experimental results. If r_m is the distance at which the plot of second moment of the activity Vs r on semi-log paper becomes straight, then,

$$\int_{r_m}^{\infty} r^2 A_s(r)\, dr = -\frac{a}{b} e^{br_m} \qquad \ldots (40)$$

$$\int_{r_m}^{\infty} r^2 . r^2 A_s(r) dr = -\frac{a}{b^3} e^{br_m}(b^2 r_m{}^2 - 2br_m + 2) \qquad \ldots (41)$$

Finally the total areas under the second moment curve and fourth moment curves are found by adding the numerical and analytical parts. The age is calculated by using Eq. (24). The age value is calculated for three different flow rates viz. (1) 18000 cc/min., (2) 36000 cc/min. and (3) 54000 cc/min.

4.3 Analysis of Statistical Errors (16)

The basic process of radioactive disintegration is statistical in nature. The statistical error in an observed number of counts N is $\pm \sqrt{N}$. The following basic rules for error estimations are used. If two

quantities R_1 and R_2 carry the statistical error $\pm$ r_1 and $\pm$ r_2 respectively then

$$\text{Error in } (R_1 \pm R_2) = \sqrt{r_1^2 + r_2^2} \quad \ldots \quad (42)$$

$$\text{Error in } R_1 R_2 = \pm R_1 R_2 \sqrt{\frac{r_1^2}{R_1^2} + \frac{r_2^2}{R_2^2}} \quad \ldots \quad (43)$$

and error in

$$\frac{R_1}{R_2} = \pm \frac{R_1}{R_2} \sqrt{\frac{r_1^2}{R_1^2} + \frac{r_2^2}{R_2^2}} \quad \ldots \quad (44)$$

Starting from the statistical error in the observed number of counts, the statistical errors in all the quantities calculated at intermediate steps in the calculation of neutron age are estimated using the basic Eqs. (42) and (43). Finally errors in the areas under non-exponential part of second moment curve and fourth moment curve are found. Errors in analytical parts of these areas have been neglected. The constants a and b are determined by a least square fit over a number of points. The statistical error in the age value is then calculated using the Eq. (43). The errors in the age values for all the three flow rates are given in Table 18.

4.4 Discussion and Results

The neutron age for the three different air flow rates viz; 18000 cc/min., 36000 cc/min. and 54000 cc/min. are given in the table (18). The volume fraction defined as the volume of air to volume of water was calculated by measuring a transition time of one second for the air bubbles. Several readings of the transition time of the bubble from the bubble tube to the water surface were noted with the help of a stop watch. The time was estimated to be one second. The neutron age for the 18000 cc. case was calculated for two mutually perpendicular directions (one parallel to bubble tubes and other perpendicular to bubble tube). With the existing geometry no remarkable difference in the age values could be noted.

It is found that the age to indium - resonance of Pu - Be neutrons will increase (compared to the value in pure water) when voids are present in water. Valente and Sullivan and P.R. Rao (at IIT Kanpur) had measured the age of Pu - Be neutrons to indium resonance in water. The age value measured in pure water by Valente and Sullivan is 52.8 ± 2.5 cm. and by P.R. Rao (at IIT Kanpur) is 53.7 ± 4.044 cm^2. As the air flow rate (or voids present in water) increases, the

age value also increases. The percentage increase in the age value for the air flow rates of 18000 cc/min., 36000 cc./min. and 54000 cc/min. are found to be 27.1% , 33.9% and 42.4% respectively.

An attempt had been made to calculate the age theoretically by using the simple formula

$$\tau = \int_{E}^{E_0} \left(\frac{D}{\xi \Sigma_s}\right) \frac{dE}{E}$$

For air flow rate of 18000 cc/min. number of nuclei/cc. of the moderator are

Water No. of nuclei/cc $= 3.34 \times 10^{22}$

Air	Oxygen	No. of nuclei/cc	$= 2.4 \times 10^{15}$
	Hydrogen	No. of nuclei/cc	$= 10.3 \times 10^{15}$
		Air weight fraction	$\simeq 5.5 \times 10^{-7}$
		Volume fraction	$\simeq 20.2 \times 10^{-5}$

This reveals that since the quantity of voids in the moderator is small, therefore if the above formula is used it will lead to the same age value as in pure water.

4.5 Sources of Errors

The inherent limitations of the experiments are (1) finite size of medium, (2) finite size of source and foils, and (3) foreign materials are needed to suspend the source and the foils. In addition to this, the factors which give rise to errors in the age measurements are due to small oscillations of foils and source which arises because of air bubbles, the errors in the distance measurement, the erros in the activities measured.

A finite medium has to be used as a reliable representation of an infinite medium. For this purpose a 4' x 4' x 4' Aluminium tank was used. When the neutron source was inside the tank, the radiation dose was measured many times in a day in all the experiments. It was found to be within permissible limits. For the finite size of source and foils an approximate correction has been applied. The errors due to the introduction of foreign materials has been minimised by using perspex for the source and foil holders and nylon threads for suspension.

The errors in distance measurements and the number of counts have been estimated. The erros in the distance measurements have been estimated to be

within $\pm$ 0.1 cm. The distances were measured with a meter scale and marked on the nylon suspension threads. The measurements were checked by several persons at different times and found to be within $\pm$ 1 mm. The errors in the activities is statistical in nature. As is well known, the error in the observed number of counts N is $\pm \sqrt{N}$. A Sample calculation is given in Appendix I.

TABLE 2. AIR FLOW RATE=18000 C.C./MIN.

DATA OF CD. COVERED IN. FOILS

DIRECTION PARALLEL TO BUBBLE TUBES

STANCE	IRRADITION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
4.1	723.0	10.0	21.0	10.0	6283	5127	110
6.5	525.0	10.0	21.0	10.0	4315	3518	110
15.8	665.0	10.0	21.0	10.0	935	612	110
22.3	627.0	10.0	21.0	10.0	316	218	110
30.2	622.0	10.0	21.0	10.0	161	147	110
36.8	767.0	10.0	21.0	10.0	143	134	120
44.8	568.0	10.0	21.0	10.0	127	125	120
47.8	500.0	10.0	21.0	10.0	124	122	120

TABLE 3. AIR FLOW RATE=18000 C.C./MIN.

DATA OF (CD.+IN.) COVERED IN. FOILS

DIRECTION PARALLEL TO BUBBLE TUBES

STANCE	IRRADITION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
4.1	780.0	10.0	21.0	10.0	3422	2600	120
6.6	600.0	10.0	21.0	10.0	2595	1840	120
15.3	734.0	10.0	21.0	10.0	590	408	120
22.3	664.0	10.0	21.0	10.0	219	170	120
30.2	690.0	10.0	21.0	10.0	141	134	125
36.3	720.0	10.0	21.0	10.0	137	132	125
44.8	630.0	10.0	21.0	10.0	129	127	125
47.8	775.0	10.0	21.0	10.0	127	126	125

TABLE 4. AIR FLOW RATE=18000 C.C./MIN.

SATURATED ACTIVITIES

DIRECTION PARALLEL TO BUBBLE TUBES

STANCE	CD. COVERED ACTIVITY	(CD.+IN.) COVERED ACTIVITY	RESONANCE ACTIVITY	ACTIVITY CORRECTED FOR FINITE SIZE OF SOURCE AND FOIL
4.1	730.00	373.03	356.98	387.00
6.6	493.02	270.02	223.00	243.00
15.8	85.01	48.56	36.45	38.40
22.3	20.02	9.49	10.53	10.84
30.2	4.37	1.60	2.77	2.80
36.8	2.37	1.19	1.18	1.20
44.8	0.77	0.39	0.38	0.39
47.8	0.39	0.20	0.19	0.20

TABLE 5. AIR FLOW RATE=18000 C.C./MIN.

CORRECTED SATURATED ACTIVITIES,2ND MOMENT,4TH MOMENT,ETC.

DIRECTION PARALLEL TO BUBBLE TUBES

DISTANCE	SATURATED ACTIVITY	2ND MOMENT OF ACTIVITY	4TH MOMENT OF ACTIVITY	LOG(2ND MOMENT OF ACTIVITY)	LOG(4TH MOMENT OF ACTIVITY)
4.1	387.0[illegible]	6505.47	139356.95	8.7804[illegible]	11.6[illegible]237
6.6	243.0[illegible]	10585.20	451095.57	9.26722	13.04136
15.8	38.40	9586.18	2393092.90	9.16808	14.68810
22.3	13.84	5390.62	2530702.14	8.59242	14.8[illegible]159
30.2	2.80	2553.71	2329087.50	7.8453[illegible]	14.66099
36.8	1.2[illegible]	1625.09	2200759.14	7.39332	14.60431
44.8	0.39	782.75	1571001.72	6.66283	14.26722
47.8	0.2[illegible]	456.97	1044098.74	6.12461	13.85866

[illegible] 6. AIR FLOW RATE=18[illegible]0 C.C./MIN.

DATA OF CO. COVERED IN. FOILS

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	IRRADITION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
5.0	475.0	10.0	21.0	10.0	5883	4772	118
7.0	501.0	10.0	21.0	10.0	4238	3338	118
9.0	647.0	10.0	21.0	10.0	2843	2310	120
11.0	604.0	10.0	21.0	10.0	2348	1051	120
15.0	60[illegible].0	10.0	21.0	10.0	879	732	120
20.0	651.0	10.0	21.0	10.0	384	318	120
25.0	690.0	10.0	21.0	10.0	2[illegible]2	181	120
30.0	763.0	10.0	21.0	10.0	165	150	120
35.0	720.0	10.0	21.0	10.0	151	138	120
40.0	793.0	10.0	21.0	10.0	131	127	120

TABLE 7. AIR FLOW RATE=18000 C.C./MIN.

DATA OF (CD.+IN.) COVERED IN. FOILS

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	IRRADITION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
5.0	455.0	10.0	21.0	10.0	3487	2703	112
7.0	423.0	10.0	21.0	10.0	2412	1796	112
9.0	480.0	10.0	21.0	10.0	1434	1073	112
11.0	449.0	10.0	21.0	10.0	944	688	115
15.0	475.0	10.0	21.0	10.0	527	402	115
20.0	525.0	10.0	21.0	10.0	249	198	115
25.0	501.0	10.0	21.0	10.0	159	144	115
30.0	551.0	10.0	21.0	10.0	135	129	115
35.0	527.0	10.0	21.0	10.0	131	127	115
40.0	577.0	10.0	21.0	10.0	121	118	115

TABLE 3. AIR FLOW RATE=18000 C.C./MIN.

SATURATED ACTIVITIES

DIRECTION PERPENDICULAR TO BUBBLE TUBES

ISTANCE	CD. COVERED ACTIVITY	(CD.+IN.) COVERED ACTIVITY	RESONANCE ACTIVITY	ACTIVITY CORRECTED FOR FINITE SIZE OF SOURCE AND FOIL
5.0	675.36	393.29	282.07	312.65
7.0	474.94	257.97	216.96	233.90
9.0	317.78	147.42	170.36	180.66
11.0	199.99	90.47	109.52	117.30
15.0	88.70	45.07	43.63	45.92
20.0	29.81	13.38	16.43	18.28
25.0	9.83	4.69	5.14	6.80
30.0	4.82	2.19	2.63	3.00
35.0	3.13	1.81	1.32	1.40
40.0	1.16	0.57	0.59	0.65

Table 12 AIR FLOW RATE=36000 C.C./MIN.

SATURATED ACTIVITIES

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	CD. COVERED ACTIVITY	(CD.+IN.) COVERED ACTIVITY	RESONANCE ACTIVITY	ACTIVITY CORRECTED FOR FINITE SIZE OF SOURCE AND FOIL
5.	7[illegible]7.95	[illegible]15.95	422.00	454.60
7.0	[illegible].[illegible]9	[illegible]47.04	314.95	326.39
9.	464.[illegible]	217.[illegible]	227.94	247.40
11.[illegible]	[illegible]54.[illegible]7	123.48	130.69	141.73
15.0	[illegible].[illegible]4	[illegible]8.07	50.07	53.30
20.0	[illegible]6.[illegible]	7.49	19.43	20.10
25.	[illegible].[illegible]7	2.49	7.98	8.14
[illegible].	5.[illegible]	1.41	3.85	3.91
[illegible]5.0	[illegible].[illegible]4	1.08	1.76	1.80
40.0	[illegible].[illegible]0	0.6[illegible]	0.87	0.89

Table 13 AIR FLOW RATE=36000 C.C./MIN.

CORRECTED SATURATED ACTIVITIES,2ND MOMENT,4TH MOMENT,ETC.

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	SATURATED ACTIVITY	2ND MOMENT OF ACTIVITY	4TH MOMENT OF ACTIVITY	LOG(2ND MOMENT OF ACTIVITY)	LOG(4TH MOMENT OF ACTIVITY)
5.0	454.60	11365.00	284125.00	9.33829	12.55717
7.0	326.39	15993.11	783662.38	9.67991	13.57173
9.0	247.40	20039.40	1623191.38	9.90546	14.29990
11.0	141.73	17149.33	2075068.92	9.74971	14.54550
15.0	53.30	11992.50	2698312.48	9.39204	14.80814
20.0	20.10	8040.00	3215999.96	8.99218	14.98365
25.0	8.14	5087.50	3179687.44	8.53454	14.97229
30.0	3.91	3519.00	3167099.96	8.16593	14.96833
35.0	1.80	2205.00	2701124.96	7.69848	14.80918
40.0	0.89	1424.00	2278400.00	7.26123	14.63898

1[illegible]. AIR FLOW RATE=36000 C.C./MIN.

DATA OF (CD.+IN.) COVERED IN. FOILS

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	IRRADITION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
5.0	525.0	10.0	21.0	10.0	2849	2274	120
7.0	551.0	10.0	21.0	10.0	2594	1897	120
9.0	578.0	10.0	21.0	10.0	2050	1553	120
11.0	610.0	10.0	21.0	10.0	1332	837	120
15.0	636.0	10.0	21.0	10.0	450	379	120
20.0	661.0	10.0	21.0	10.0	234	173	130
25.0	686.0	10.0	21.0	10.0	155	144	130
30.0	715.0	10.0	21.0	10.0	144	138	[illegible]
35.0	750.0	10.0	21.0	10.0	141	136	130
40.0	785.0	10.0	21.0	10.0	137	133	130

Table 12 [illegible] ./ 1[illegible].

[illegible]

[illegible]

DISTANCE	[illegible] ACTIVITY	[illegible] ACTIVITY	[illegible] ACTIVITY	ACTIVITY CORRECTED FOR FINITE SIZE [illegible] SOURCE AND FOIL
5.[illegible]	[illegible]	[illegible]	[illegible].00	[illegible]
7.[illegible]	[illegible]	[illegible]	[illegible].95	[illegible]
9.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1[illegible].	[illegible]	[illegible]	[illegible].40	[illegible]
[illegible]5.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3[illegible].[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
35.[illegible]	[illegible]	[illegible]	[illegible].76	[illegible]
40.[illegible]	[illegible]	[illegible]	.27	[illegible]

Table 13 [illegible]

[illegible]

[illegible]

DISTA[illegible]	[illegible] ACTIVITY	[illegible] OF ACTIVITY	[illegible]TH MOMENT OF ACTIVITY	LOG([illegible]MOMENT OF ACTIVITY)	LOG([illegible]) OF ACTIVITY
5.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.[illegible]
7.[illegible]	[illegible]	[illegible]	[illegible]	4.6799	[illegible]
9.0	[illegible]	[illegible]	[illegible]19.[illegible]	[illegible]	[illegible]
11.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2[illegible]	[illegible]	[illegible]	[illegible].98	[illegible]	[illegible]
25.0	[illegible]	[illegible]	[illegible].44	[illegible]	[illegible]
3[illegible]	[illegible]	[illegible]	[illegible].96	[illegible]	[illegible]
35.[illegible]	[illegible]	[illegible]	[illegible].96	[illegible]	[illegible]
4[illegible]	[illegible]	[illegible]	[illegible].00	[illegible]	[illegible]

14. AIR FLOW RATE=54000 C.C./MIN.

DATA OF CD. COVERED IN. FOILS

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	IRRADIATION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
5.0	465.0	10.0	21.0	10.0	6387	5275	120
7.0	592.0	10.0	21.0	10.0	4575	3903	120
9.0	490.0	10.0	21.0	10.0	4003	3187	120
11.0	617.0	10.0	21.0	10.0	2471	1760	120
15.0	515.0	10.0	21.0	10.0	810	737	120
20.0	585.0	10.0	21.0	10.0	434	363	120
25.0	603.0	10.0	21.0	10.0	232	195	120
30.0	790.0	10.0	21.0	10.0	177	157	120
35.0	627.0	10.0	21.0	10.0	153	134	120
40.0	655.0	10.0	21.0	10.0	137	130	120

[illegible] 15. AIR FLOW RATE=54000 C.C./MIN.

DATA OF (CD.+IN.) COVERED IN. FOILS

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	IRRADITION TIME	WAITING TIME 1ST SIDE	WAITING TIME 2ND SIDE	COUNTING TIME	NUMBER OF COUNTS 1ST SIDE	NUMBER OF COUNTS 2ND SIDE	BACKGROUND COUNTS
5.0	416.0	10.0	21.0	10.0	3317	2484	130
7.0	525.0	10.0	21.0	10.0	2356	1833	130
9.0	441.0	10.0	21.0	10.0	2268	1701	130
11.0	465.0	10.0	21.0	10.0	1118	824	130
15.0	533.0	10.0	21.0	10.0	460	347	130
20.0	490.0	10.0	21.0	10.0	268	226	133
25.0	710.0	10.0	21.0	10.0	161	151	133
30.0	56[illegible].0	10.0	21.0	10.0	149	143	133
35.0	75[illegible].0	10.0	21.0	10.0	145	141	135
40.0	785.0	10.0	21.0	10.0	143	139	135

TABLE 16 AIR FLOW RATE=54.[illegible] C.C./MIN.

SATURATED ACTIVITIES

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	CD. COVERED ACTIVITY	(CD.+IN.) COVERED ACTIVITY	RESONANCE ACTIVITY	ACTIVITY CORRECTED FOR FINITE SIZE OF SOURCE AND FOIL
5.0	741.04	358.97	382.06	433.93
7.0	534.00	253.93	280.07	299.96
9.0	449.93	239.92	210.01	222.8[illegible]
11.0	256.90	108.53	148.36	156.45
15.0	91.02	35.16	55.85	58.52
20.0	35.94	14.69	21.25	22.17
25.0	12.02	2.95	9.07	9.34
30.0	6.04	1.92	4.11	4.14
35.0	2.97	1.03	1.95	1.99
40.0	1.73	0.77	0.96	1.[illegible]

TABLE 17. AIR FLOW RATE=540.0 C.C./MIN.

CORRECTED SATURATED ACTIVITIES,2ND MOMENT,4TH MOMENT,ETC.

DIRECTION PERPENDICULAR TO BUBBLE TUBES

DISTANCE	SATURATED ACTIVITY	2ND MOMENT OF ACTIVITY	4TH MOMENT OF ACTIVITY	LOG(2ND MOMENT OF ACTIVITY)	LOG(4TH MOMENT OF ACTIVITY)
5.0	423.90	10597.50	264937.50	9.26837	12.48725
7.0	299.95	14697.55	720179.94	9.59544	13.48726
9.0	222.80	18046.80	146179[illegible].78	9.80072	14.19517
11.0	156.45	18930.45	2290584.42	9.84853	14.64432
15.0	58.52	13167.30	2962574.96	9.48547	14.90157
20.0	22.17	8868.40	3547360.00	9.09025	15.08173
25.0	9.34	5836.87	3648046.84	8.67195	15.1[illegible]97[illegible]
30.0	4.14	3730.50	3357449.96	8.2243	15.[illegible]2669
35.0	1.99	2437.75	298624[illegible].68	7.79887	14.9095[illegible]
40.0	1.00	1596.80	2554880.00	7.37576	14.75352

TABLE 18. AGE VALUES IN AIR WATER MIXTURES

S.No.	Air Flow Rate cc/mm.	Volume fraction (approx.) ($\times 10^{-5}$)	Direction*	$A_s r^2$ curve total area ($\times 10^5$)	$A_s r^4$ curve total area ($\times 10^7$)	Age cm^2
1	18,000	20.2	A	2.6543 ± 0.1991	10.9559 ± 0.3446	68.79 ± 3.57
2	18,000	20.2	B	2.5642 ± 0.1007	10.3359 ± 0.2998	67.18 ± 3.28
3	36,000	40.4	B	3.2931 ± 0.09847	13.9816 ± 0.2909	70.76 ± 2.57
4	54,000	60.6	B	3.3547 ± 0.1054	15.1546 ± 0.3289	75.28 ± 2.87

* A : Parallel to Bubble tubes

B : Perpendicular to Bubble tubes

BIBLIOGRAPHY

1. Dorner et.al, N.S.E., 9, p. 221 (1961).
2. J.W. Cooper, N.S.E., 10, p. 1 (1961)
3. Amster and Gast, N.S.E., 11, p. 167 (1961).
4. De Juren et al, N.S.E., 11, p. 179 (1961).
5. Amster and Gast, N.S.E., 11, p. 192 (1961).
6. Joanou et al, N.S.E., 13, p. 171 (1962).
7. R.K. Paschall, N.S.E., 20, p. 436 (1964).
8. Mary Alter, N.S.E., 23, p. 264 (1965).
9. Kallimullah, M.Tech. Thesis, Mech. Engg. Deptt., IIT Kanpur, p. , July (1970).
10. P.R. Rao, M.Tech. Thesis, Mech. Engg. Deptt., IIT Kanpur, pp. 24,27-28 (1970).
11. P.R. Rao, M.Tech. Thesis, Mech. Engg. Deptt., IIT Kanpur, pp.26 (1960).
12. F.A. Valente, A Manual of Experiments in Reactor Physics, The McMillan Company, N.Y., p.90 (1963).
13. F.A. Valente, A Manual of Experiments in Reactor Physics, The McMillan Company, N.Y., p.64 (1963).
14. P.F. Palmedo, N.S.E., 32, p.310 (1968).
15. Kaimullah, M.Tech. Thesis, Mech. Engg. Deptt., IIT Kanpur, pp. 40 (July, 1970).
16. F.A. Valente, A Manual of Experiments in Reactor Physics, The McMillan Company, N.Y., pp.36-38 (1963).

APPENDIX

SAMPLE CALCULATIONS

The procedure for calculating age of Pu - Be neutron to Indium resonance along with sample calculations for air flow rate of 18,000 cc/min. is given below.

Procedure

1. Draw graphs Fig. 16a, 16b, 16c from Table 8.
2. Take values from these graphs and calculate error
3. Form Table 19
4. From Table 19 find area under non-exponential part of 2nd and 4th moment curves
5. Find area under exponential part of 2nd and 4th moment curves
6. Find total area under 2nd and 4th moment curves
7. Find error in area under 2nd an[illegible] curves
8. Calculate age and error in age.

Error in A_s, 2nd Moment and 4th Moment

From Figure 16a, 16b, and 16c we get the following values

r	C_d covered activity	C_d+I_n covered activity	Corrected activity A_s
24	10	5	6

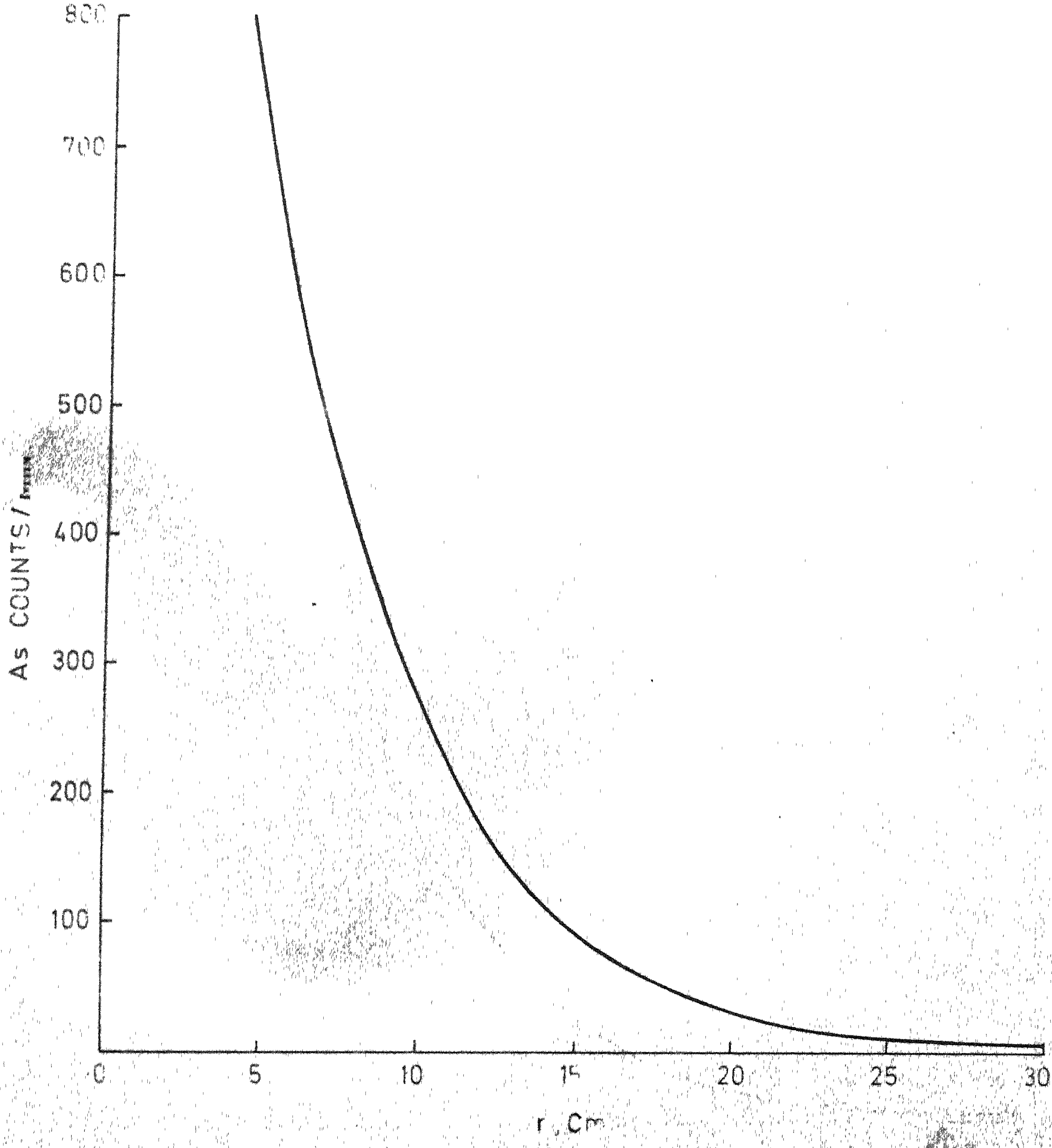


FIG 16(a). GRAPH OF As Vs r FOR CD. COVERED INDIUM FOILS FOR AIR FLOW RATE OF 18000 C.C./MIN IN A DIRECTION PERPENDICULAR TO BUBBLETUBES

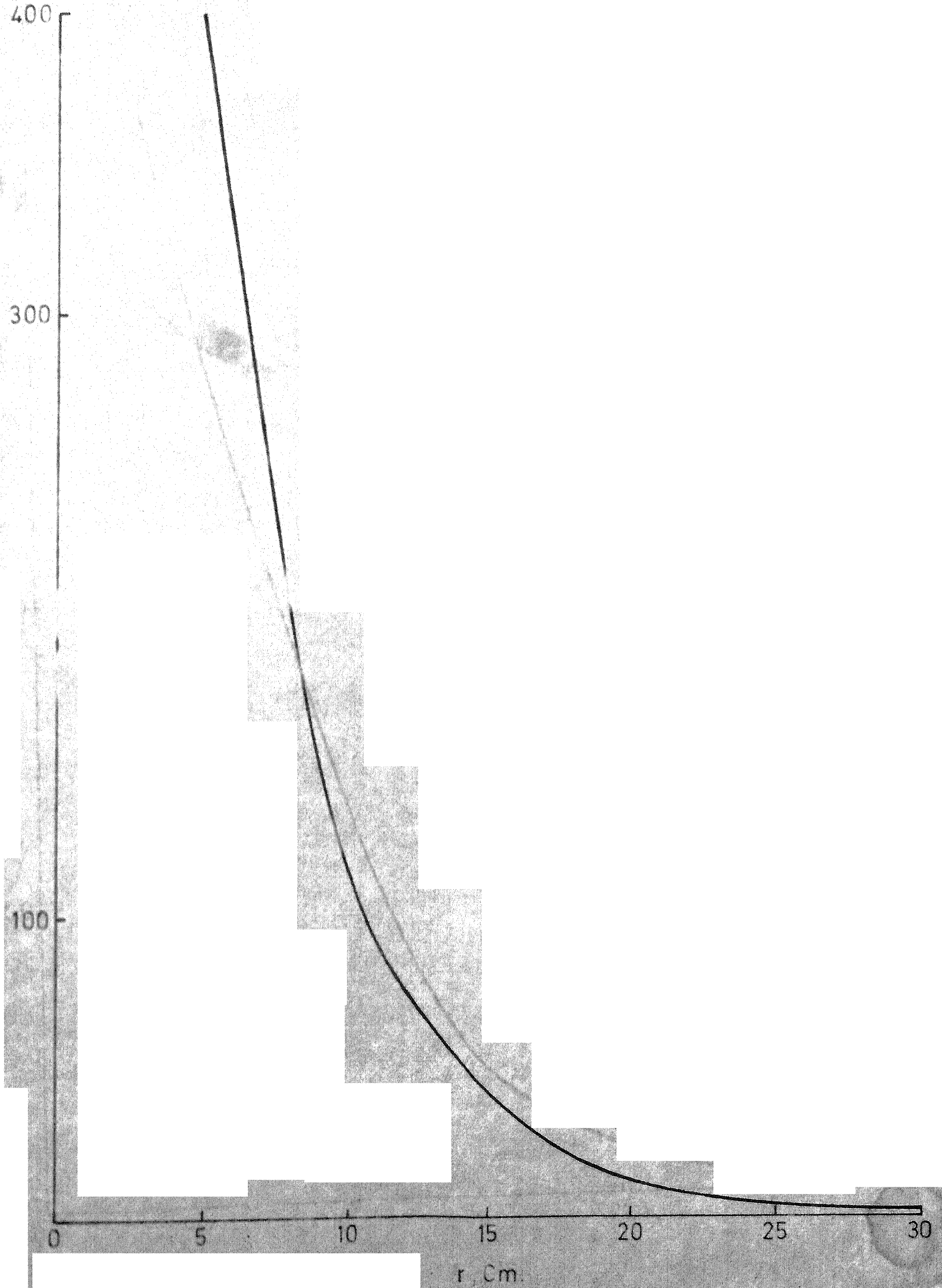


FIG.16(b). GRAPH OF As Vs. r FOR (CD. + IN.) COVERED INDIUM FOILS FOR AIR FLOW RATE OF 18000 C.C./MIN. IN A DIRECTION PERPENDICULAR TO BUBBLE TUBES.

From Table 19

Using Eq. (45) we get area under 2nd moment curve for

$\delta x = 2$ cm as

$(\text{Area})_{1\ \text{Non Exp.}} = 2.0607 \times 10^5$

and also the area under 4th moment curve as

$(\text{Area})_{2\ \text{Non Exp.}} = 3.7001 \times 10^7$

Area Under Exponential Part of 2nd Moment and 4th Moment Curve

From Table 9 we can calculate the values of

Least square constant $A = 4.446 \times 10^5$ and of

Least square constant $B = -0.935 \times 10^{-1}$

Using Eq. (40) and Eq. (41) we get area under 2nd moment curve as

$$(\text{Area})_{1\ \text{Exp.}} = \int_{24}^{\infty} A\, e^{BX} = .5036 \times 10^5$$

and area under 4th moment curve as

$$(\text{Area})_{2\ \text{Exp.}} = \int_{24}^{\infty} r^2\, A\, e^{BX} = 6.6359 \times 10^7$$

Total Area Under 2nd Moment and 4th Moment Curves

Under 2nd moment ($A_s r^2$) curve

$$\text{Total Area} = (\text{Area})_{1\ \text{Non Exp.}} + (\text{Area})_{1\ \text{Exp.}}$$

$$= 2.5643 \times 10^5$$

Under 4th moment ($A_{sl} r^4$) curve

$$\text{Total area} = (\text{Area})_{2\ \text{Non Exp.}} + (\text{Area})_{2\ \text{Exp.}}$$

$$= 10.3360 \times 10^7$$

From these we get the errors from Eq. (42) as

$$E\,A_s = (10 + 5)^{1/2} = \pm\, 3.87$$ and

from Eq. (43) as

$$E\,A_s r = 6 \times 24 \left(\frac{3.87^2}{6^2} + \frac{0.10^2}{24^2}\right)^{1/2} = \pm\, 93.0$$

$$E\,A_s r^2 = EX(12) = 6 \times 24 \times 24 \left[\frac{(93.0)^2}{(6\times24)^2} + \frac{0.1^2}{24^2}\right]^{1/2}$$

$$= \pm\, 0.223 \times 10^4$$

$$E\,A_s r^3 = 6 \times 24 \times 24 \times 24 \left[\frac{(3230)^2}{(6\times24\times24)^2} + \frac{0.1^2}{24^2}\right]^{1/2}$$

$$= 5.4 \times 10^4$$

$$E\,A_s r^4 = EY(12) = 6 \times 24 \times 24 \times 24 \times 24$$

$$\left[\frac{(54000)^2}{(6\times24\times24\times24)^2} + \frac{0.1^2}{24^2}\right]^{1/2}$$

$$= 0.1285 \times 10^6$$

Area Under Non-Exponential Part of 2nd Moment and 4th Moment Curve

Simpon's rule for area under the curve for 12 equally spaced interval is given by

$$\text{Area} = \frac{\delta x}{3}\left[y_0 + 4y_1 + 2y_2 + 4y_3 + 2y_4 + 4y_5 + 2y_6 + 4y_7 + 2y_8 + 4y_9 + 2y_{10} + 4y_{11} + y_{12}\right] \quad \ldots (45)$$

TABLE 19. VALUES OF SATURATED ACTIVITIES, 2ND MOMENT AND 4TH MOMENT WITH THEIR ASSOCIATED ERRORS FOR AIR FLOW RATE OF 18,000 CC/MIN.

I	r	$A_s \pm EA_s^*$	$\left[A_s r^2 \pm EX^*(I)\right] 10^4$	$\left[A_s r^4 \pm EY^*(I)\right] 10^6$
1	2 ± 0.1	460 ± 41.71	0.184 ± 0.021	0.00735 ± 0.00099
2	4 ± 0.1	360 ± 36.05	0.576 ± 0.061	0.09216 ± 0.01031
3	6 ± 0.1	272 ± 29.56	0.979 ± 0.109	0.35251 ± 0.04007
4	8 ± 0.1	210 ± 23.87	1.344 ± 0.154	0.86016 ± 0.10012
5	10 ± 0.1	148 ± 19.18	1.480 ± 0.192	1.48000 ± 0.19410
6	12 ± 0.1	94 ± 15.52	1.353 ± 0.224	1.94918 ± 0.32354
7	14 ± 0.1	60 ± 12.84	1.176 ± 0.252	2.30496 ± 0.49604
8	16 ± 0.1	38 ± 10.44	0.972 ± 0.267	2.49036 ± 0.68492
9	18 ± 0.1	27 ± 8.36	0.874 ± 0.271	2.83435 ± 0.87885
10	20 ± 0.1	17 ± 7.74	0.679 ± 0.309	2.72000 ± 0.12396
11	22 ± 0.1	10 ± 5.00	0.484 ± 0.242	2.34256 ± 0.11714
12	24 ± 0.1	6 ± 3.87	0.345 ± 0.223	1.990656 ± 0.12850

* EA_s is error in A_s

* $EX(I)$ is error in $A_s r^2$

* $EY(I)$ is error in $A_s r^4$

From Table 19

Using Eq. (45) we get area under 2nd moment curve for

$\delta x = 2$ cm as

$(Area)_{1\ Non\ Exp.} = 2.0607 \times 10^5$

and also the area under 4th moment curve as

$(Area)_{2\ Non\ Exp.} = 3.7001 \times 10^7$

<u>Area Under Exponential Part of 2nd Moment and 4th Moment Curve</u>

From Table 9 we can calculate the values of

Least square constant $A = 4.446 \times 10^5$ and of

Least square constant $B = -0.935 \times 10^{-1}$

Using Eq. (40) and Eq. (41) we get area under 2nd moment curve as

$$(Area)_{1\ Exp.} = \int_{24}^{\infty} A\ e^{BX} = .5036 \times 10^5$$

and area under 4th moment curve as

$$(Area)_{2\ Exp.} = \int_{24}^{\infty} r^2\ A\ e^{BX} = 6.6359 \times 10^7$$

<u>Total Area Under 2nd Moment and 4th Moment Curves</u>

Under 2nd moment $(A_s r^2)$ curve

$$\text{Total Area} = (Area)_{1\ Non\ Exp.} + (Area)_{1\ Exp.}$$

$$= 2.5643 \times 10^5$$

Under 4th moment $(A_{sI} r^4)$ curve

$$\text{Total area} = (Area)_{2\ Non\ Exp.} + (Area)_{2\ Exp.}$$

Errors in Areas Under 2nd and 4th Moment Curves

From Table 19 and by using Eq. (42) and Eq. (45) we get error under 2nd moment curve as

$$E(Area)_1 = \left[\frac{\delta x}{3}\left\{EX(0)^2 + 4EX(1)^2 + 2EX(2)^2 + \ldots + EX(12)^2\right\}\right]^{1/2}$$

$$= \pm\ 0.1008 \times 10^5$$

and error under 4th moment curve as

$$E(Area)_2 = \left[\frac{\delta x}{3}\left\{EY(0)^2 + 4EY(1)^2 + 2EY(2)^2 + \ldots + EY(12)^2\right\}\right]^{1/2}$$

$$= \pm\ 0.2999 \times 10^7$$

Age and Error in Age

From above we get

$$(Area)_1 = (2.564 \pm 0.1008) \times 10^5$$

$$(Area)_2 = (10.336 \pm 0.2999) \times 10^7$$

$$Age = \frac{1}{6} \times \frac{10.3360 \times 10^7}{2.5643 \times 10^5}\ cm^2$$

Error in age with the help of Eq. (44) is

$$E\ Age = \pm\ 3.28\ cm^2$$

Therefore

Age Value = $67.13 \pm 3.28\ cm^2$

APPENDIX II

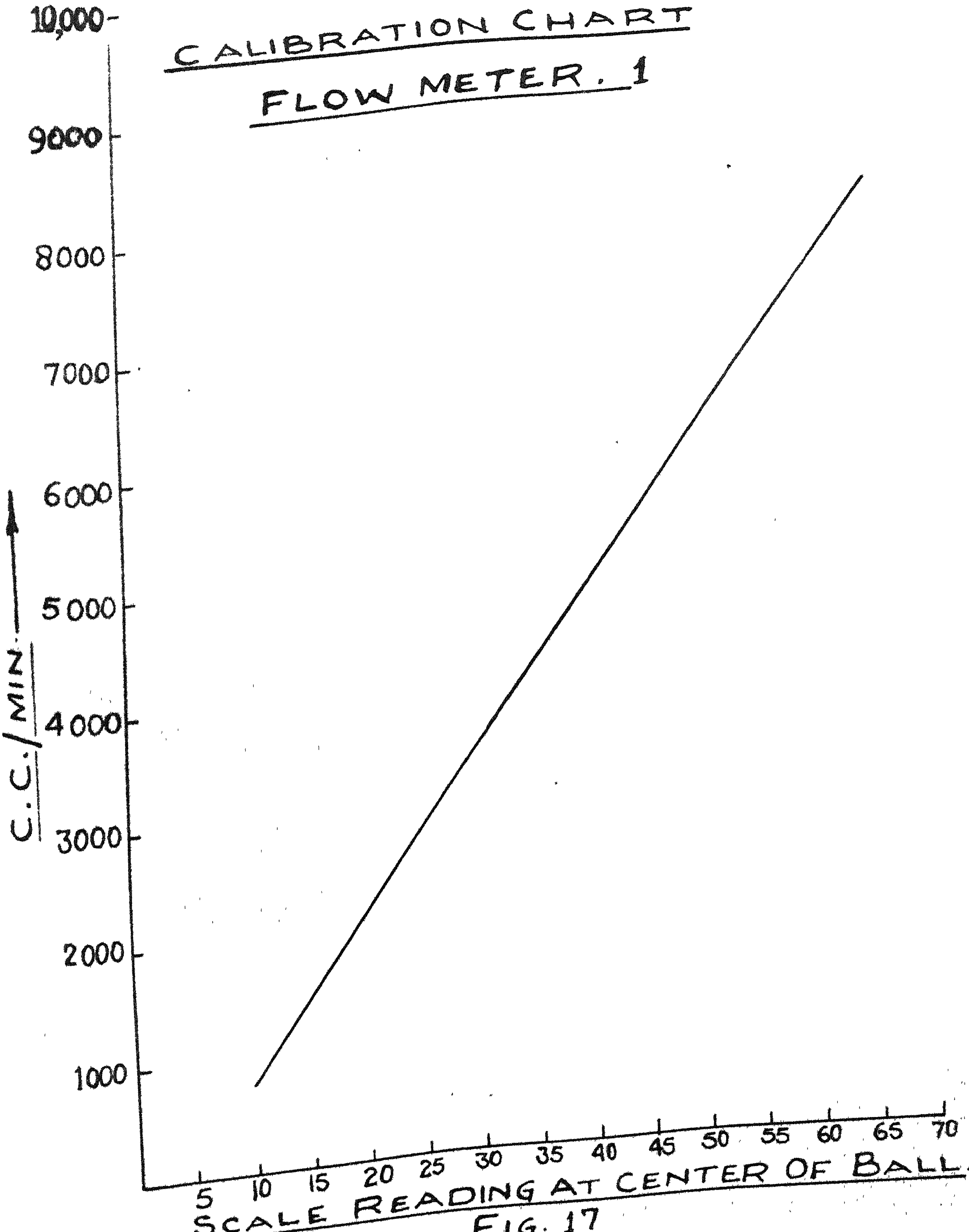

CALIBRATION CHART
FLOW METER. 1
C.C./MIN.
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
5
10
15
20
25
30
35
40
45
50
55
60
65
70
SCALE READING AT CENTER OF BALL.

FIG. 17

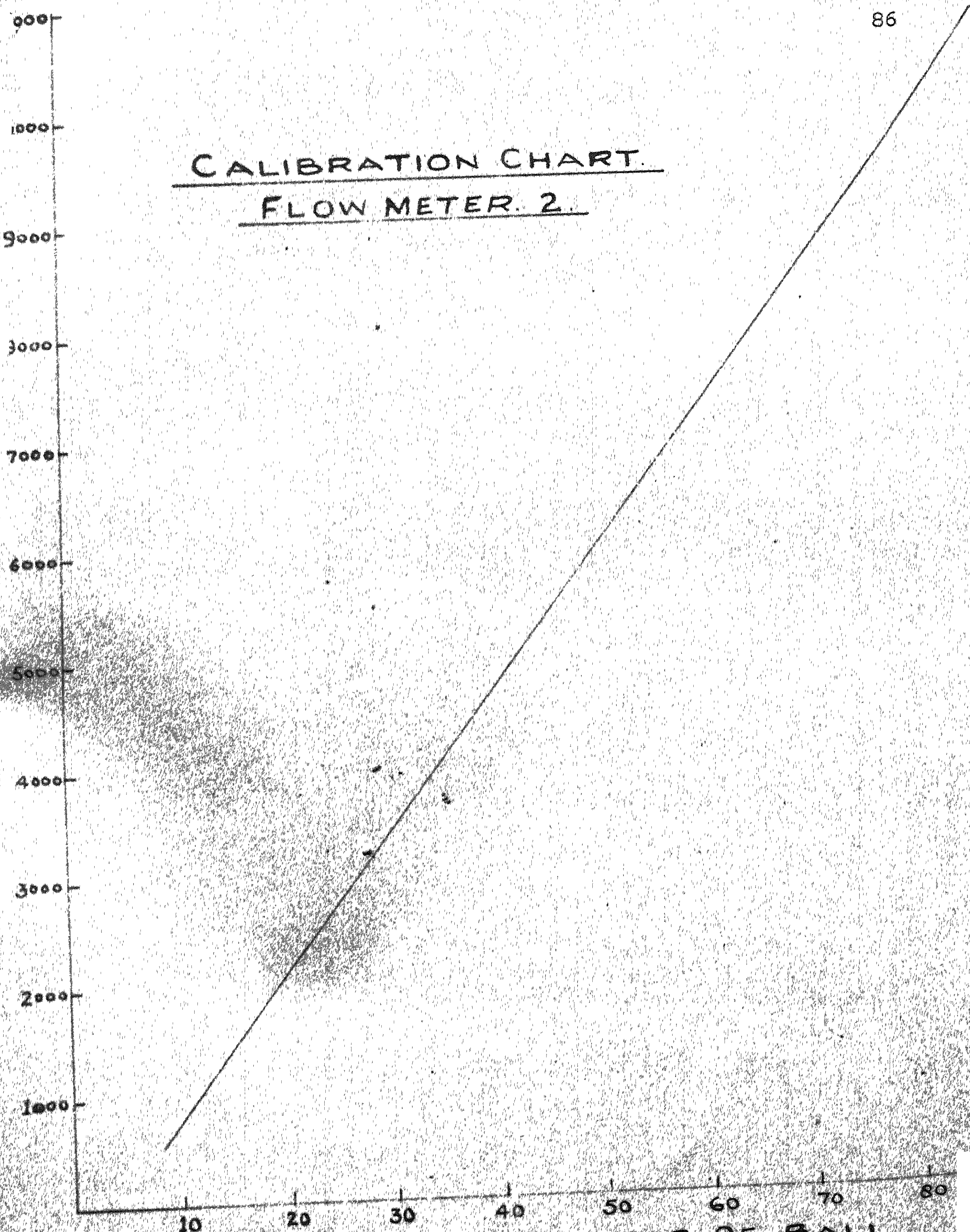
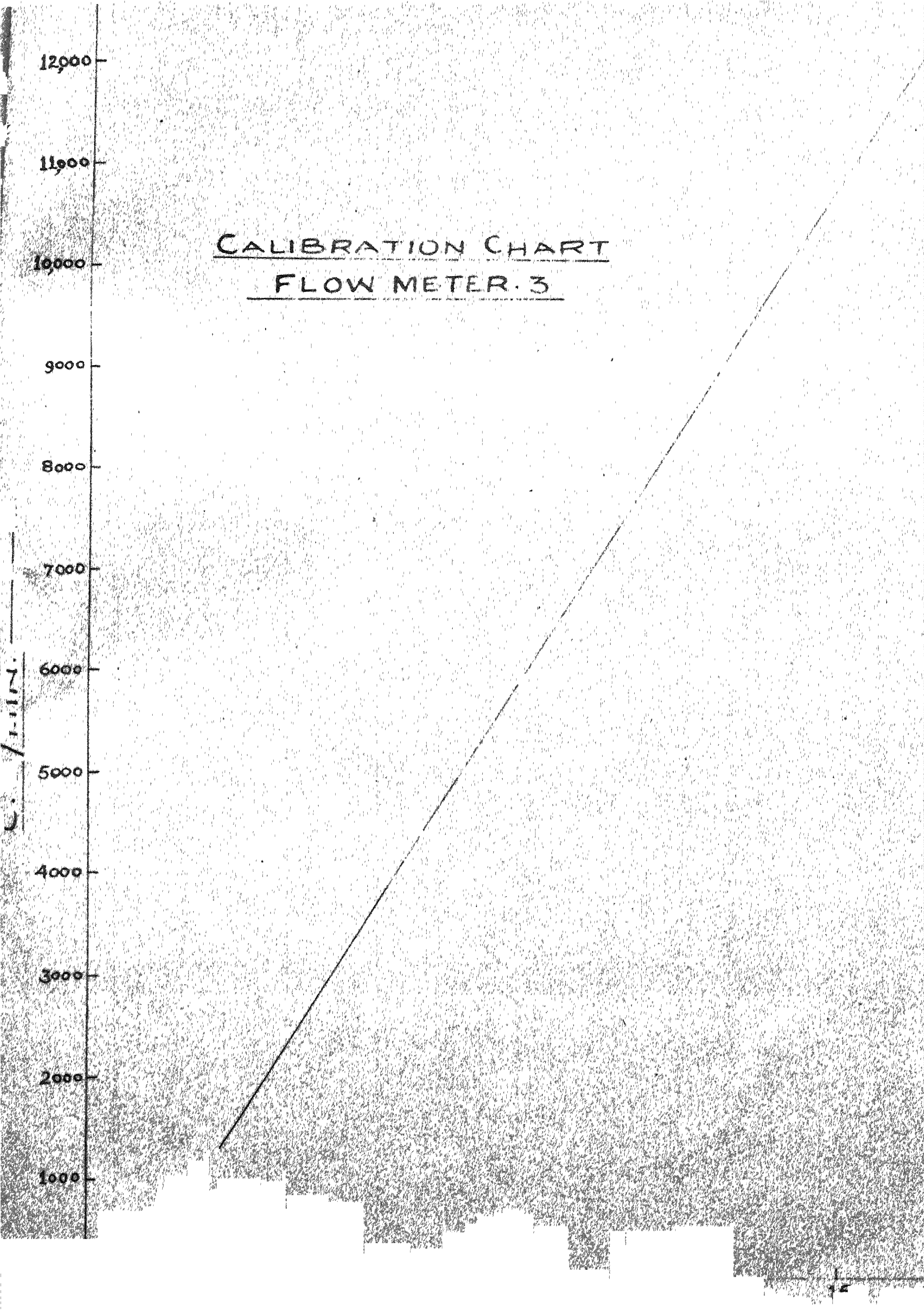
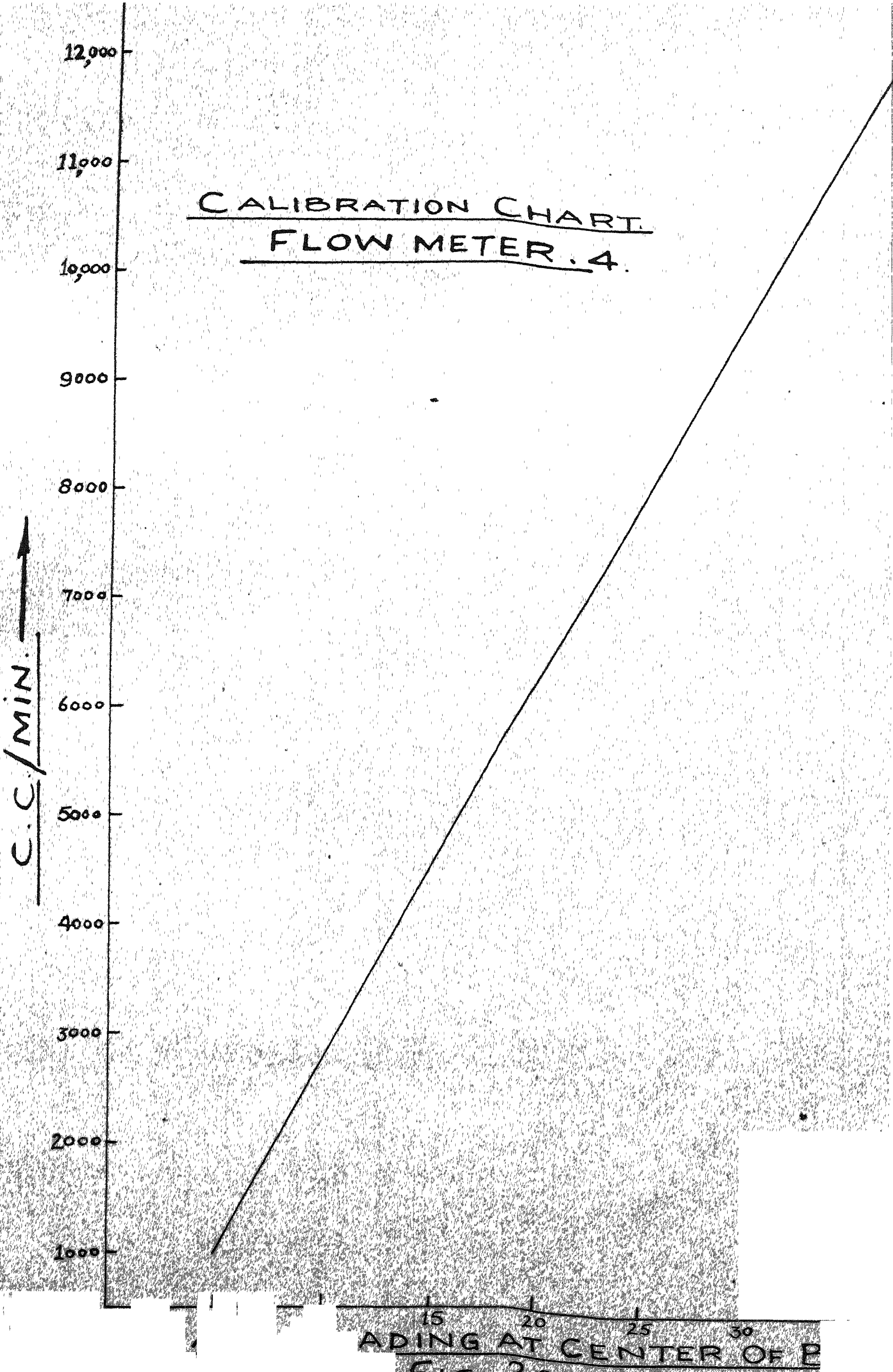
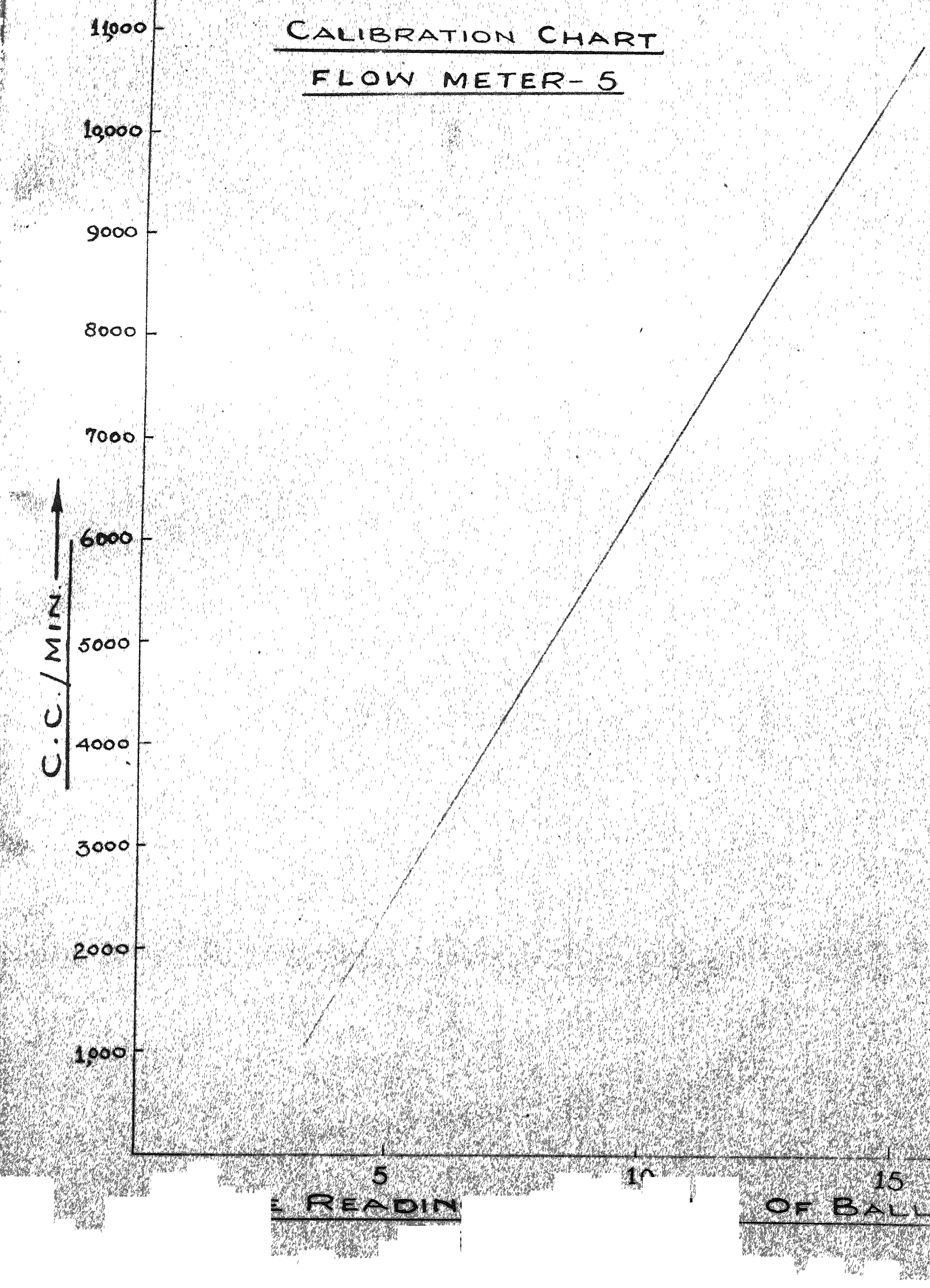
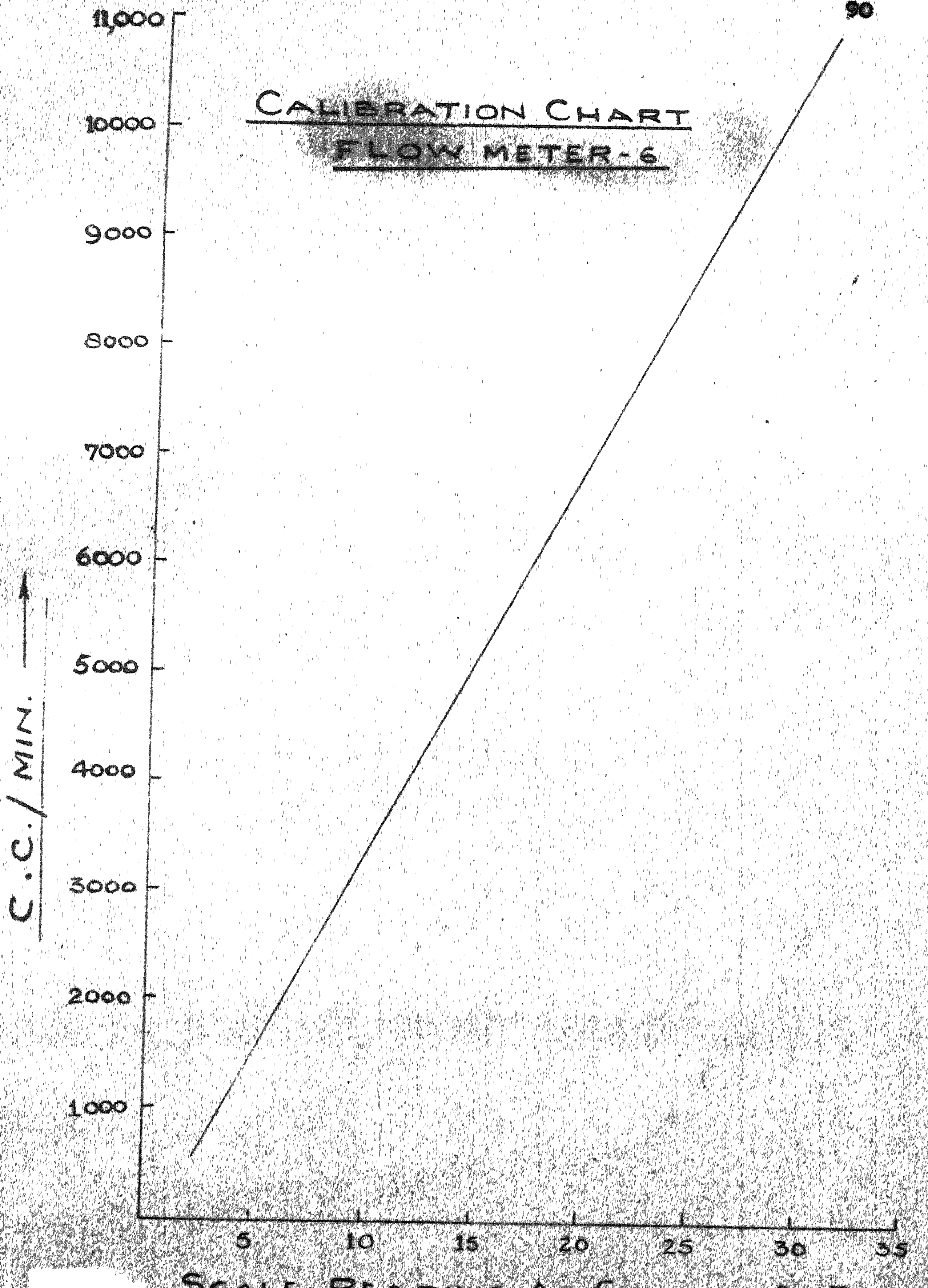

CALIBRATION CHART.
FLOW METER. 2.
9000
8000
7000
6000
5000
4000
3000
2000
1000
10
20
30
40
50
60
70
80
SCALE READING AT CENTER OF BALL.

FIG. 18


CALIBRATION CHART
FLOW METER · 3
12,000
11,000
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000


CALIBRATION CHART
FLOW METER . 4
12,000
11,000
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
C.C./MIN.
15
20
25
30
ADING AT CENTER OF B
FIG. 20


CALIBRATION CHART
FLOW METER- 5
C.C./MIN.
11,000
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1,000
5
10
15
READIN
OF BALL


CALIBRATION CHART
FLOW METER-6
11,000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
C.C./MIN.
90
5
10
15
20
25
30
35
SCALE READING AT CENTER OF BALL

F 2